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NATIONAL ENERGY TECHNOLOGY LABORATORY

Field Test Program to Develop Comprehensive Design, Operating, and Cost Data for Mercury Control Systems

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ABSTRACT

With the nation's coal-burning utilities facing the possibility of tighter controls on mercury pollutants, the U.S. Department of Energy is funding projects that could offer power plant operators better ways to reduce these emissions at much lower costs.

Mercury is known to have toxic effects on the nervous systems of humans and wildlife. Although it exists only in trace amounts in coal, mercury is released when coal burns and can accumulate on land and in water. In water, bacteria transform the metal into methylmercury, the most hazardous form of the metal. Methylmercury can collect in fish and marine mammals in concentrations hundreds of thousands times higher than the levels in surrounding waters.

One of the goals of DOE is to develop technologies by 2005 that will be capable of cutting mercury emissions 50 to 70 percent at well under one-half of projected DOE/EPA early cost estimates. ADA Environmental Solutions (ADA-ES) is managing a project to test mercury control technologies at full scale at four different power plants from 2000 – 2003. The ADA-ES project is focused on those power plants that are not equipped with wet flue gas desulfurization systems.

ADA-ES has developed a portable system that was tested at four different utility power plants. Each of the plants is equipped with either electrostatic precipitators or fabric filters to remove solid particles from the plant's flue gas.

ADA-ES's technology injects a dry sorbent, such as activated carbon, which removes the mercury and makes it more susceptible to capture by the particulate control devices.

PG&E National Energy Group provided two test sites that fire bituminous coals and both are equipped with electrostatic precipitators and carbon/ash separation systems. Wisconsin Electric Power Company provided a third test site that burns Powder River Basin (PRB) coal and has an electrostatic precipitator for particulate control. Alabama Power Company hosted a fourth test at its Plant Gaston, which is equipped with a hot-side electrostatic precipitator and a downstream fabric filter.

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INTRODUCTION

On March 15, 2005, the U.S. Environmental Protection Agency (EPA) issued the Clean Air Mercury Rule to permanently cap and reduce mercury emissions from coal-fired power plants. These regulations are directed at the existing fleet of nearly 1,100 existing boilers. These plants are relatively old with an average age of over 40 years. Although most of these units are capable of operating for many additional years, there is a desire to minimize large capital expenditures because of the reduced (and unknown) remaining life of the plant to amortize the project.

In addition, utilities are being faced with operating in an unregulated competitive environment in which they must strive to be the low-cost provider. Since the cost of fuel represents approximately 70% of the incremental cost of generating electricity, it is critical that the plant be able to purchase the cheapest fuels available.

Besides reducing fuel costs, power plants have extensively trimmed operating personnel at the plants in a further attempt to reduce operating expenses. At the same time, coal is available from U.S. reserves and is one of the most economical sources of power, so that keeping these plants operating reliably is critical, especially during peak demand periods.

Therefore, the industry needs environmental control technologies that will have the following fundamental characteristics:

- Will take advantage as much as possible of existing equipment and minimize the need for installing new major capital equipment,
- Can effectively meet regulations on a wide variety of coal characteristics,
- Will not require additional manpower or specialized technical expertise, and
- Can be installed and operated without jeopardizing the reliability of the generating facility.

With regulations now in place, it is important to concentrate efforts on the most mature retrofit control technologies. Injection of dry sorbents such as powdered activated carbon (PAC) into the flue gas and further collection of the sorbent by electrostatic precipitators (ESPs) and fabric filters (FFs) is commonly used in municipal waste incinerators for mercury control and represents the most mature and potentially most cost-effective control technology for power plants.

Under a cooperative agreement from the Department of Energy National Energy Technology Laboratory (DOE/NETL), ADA-ES, Inc., worked in partnership with PG&E National Energy Group (NEG), We Energies (a subsidiary of Wisconsin Energy Corporation (WEC)), Alabama Power Company (a subsidiary of Southern Company), Ontario Power Generation, Tennessee Valley Authority, FirstEnergy Corp., and EPRI on a field test program of sorbent injection technology for mercury control.

Four full-scale demonstrations were conducted during 2001 and 2002. The four sites, shown in Table 1, fire a coal type and have particulate control equipment that are representative of 75% of the coal-fired generation in the United States. The first program was completed in the spring of 2001 at the Alabama Power E.C. Gaston Station. This unit burns a low-sulfur bituminous coal and uses a hot-side ESP followed by a COHPAC® fabric filter for particulate control. Activated carbon was injected into the COHPAC® fabric filter. The second program was conducted during the fall of 2001 at the WEC Pleasant Prairie Power Plant (PPPP). This unit burns a subbituminous Powder River Basin (PRB) coal and uses an electrostatic precipitator to collect the carbon and fly ash. The third program was completed in the summer of 2002 at PG&E National Energy Group's Brayton Point Station. This unit burns low-sulfur bituminous coals and uses electrostatic precipitators for particulate control. The fourth program was completed in the fall of 2002 at PG&E National Energy Group's Salem Harbor Station. Salem Harbor fires bituminous coals with an ESP for particulate control and has a selective non-catalytic reduction (SNCR) system for NO_x control. The test programs are described in detail in separate reports (DOE Topical Report Numbers 41005R11, 41005R12, 41005R18, 41005R21). This report summarizes results from the entire program.

Table 1. Project Test Sites.

Test Site	Coal	Particulate Control
PG&E NEG Salem Harbor	Low-sulfur bituminous	Cold-Side ESP
PG&E NEG Brayton Point	Low-sulfur bituminous	Cold-Side ESP
We Energies Pleasant Prairie	PRB (subbituminous)	Cold-Side ESP
Alabama Power Gaston	Low-sulfur bituminous	Hot-Side ESP COHPAC® FF

EXECUTIVE SUMMARY

Under a cooperative agreement from the Department of Energy National Energy Technology Laboratory (DOE/NETL), ADA-ES, Inc., worked in partnership with PG&E National Energy Group (NEG), We Energies (a subsidiary of Wisconsin Energy Corporation), Alabama Power Company (a subsidiary of Southern Company), Ontario Power Generation, Tennessee Valley Authority, FirstEnergy Corp., and EPRI on a field test program of sorbent injection technology for mercury control.

Four full-scale demonstrations were conducted during 2001 and 2002. The four sites chosen for testing fire coal types and have particulate control equipment that are representative of 75% of the coal-fired generation in the United States. The first program was completed in the spring of 2001 at the Alabama Power E.C. Gaston Station. The second program was conducted during the fall of 2001 at the We Energies Pleasant Prairie Power Plant (PPPP). The third program was completed in the summer of 2002 at PG&E National Energy Group's Brayton Point Station. The fourth program was completed in the fall of 2002 at PG&E National Energy Group's Salem Harbor Station. Tests were conducted on a portion of the gas stream of each unit, with flows ranging from 260,000 to 600,000 acfm, or the equivalent of 44 MWs to 150 MWs. The individual site test programs and results are described in detail in separate reports (DOE Topical Report Numbers 41005R11, 41005R12, 41005R18, 41005R21).

Parameters evaluated in this program included:

- Electrostatic precipitator configuration;
- Fabric filter, in the COHPAC® configuration;
- Eastern low-sulfur bituminous coals;
- PRB coal;
- Activated carbon injection concentrations, from 1 to 30 lbs/MMacf;
- Activated carbons and ash-based sorbents from different suppliers;
- Flue gas temperatures, (lowered temperature by spray cooling and increased temperature by the use of steam coils);
- Selective non-catalytic reduction (SNCR) for NO_X control on and off;
- SO_3 conditioning on and off; and
- LOI carbon percentage.

Test results showed that fabric filters and ESPs have distinctly different mercury removal characteristics. This was expected because the dust cake on a fabric filter bag provides a better mechanism for contact between vapor-phase mercury in the flue gas and the activated carbon particles than what occurs in an ESP. Testing also showed that with an ESP,

activated carbon performance is different when low sulfur bituminous coals are fired versus PRB coals. These performance trends are summarized in Figure 1.

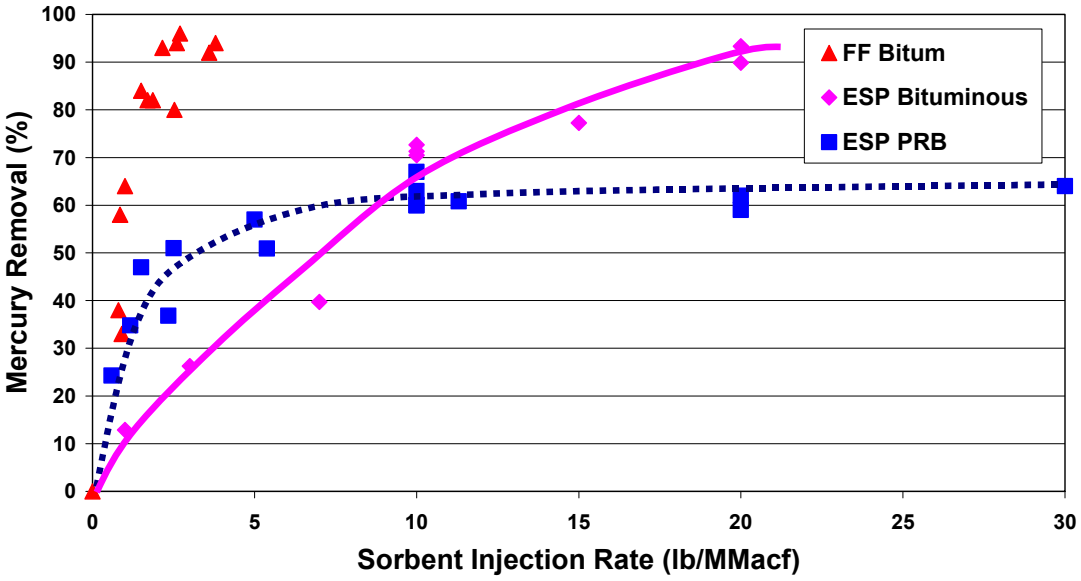

Figure 1. Activated Carbon Performance on Mercury Removal in ESPs and Fabric Filters.

This set of curves became the point of reference for a number of groups debating mercury control regulations, including DOE, EPA, utility MACT working group, state regulators, national policy developers and other researchers. Data from this program provided a basis for more meaningful discussions regarding activated carbon injection technology, its capabilities, cost, and information gaps relative to a utility mercury regulation.

Some of the major conclusions from this program included:

- Activated carbon injection achieved up to 90% mercury removal for short operating periods on a COHPAC® fabric filter.
- An average of 78% removal was achieved over a ten-day period at a lower than optimum injection rate on a COHPAC fabric filter.
- Using standard non-treated activated carbons, 70% mercury removal was achieved on an ESP with PRB coal.
- Using non-treated activated carbons, 90% mercury removal was achieved on an ESP with low sulfur bituminous coal.
- Activated carbon effectively removed both elemental and oxidized forms of mercury on both bituminous and PRB coals.
- Typical capital costs for activated carbon systems were estimated to be <$3/kW.
- Annual sorbent costs were estimated to be between $0.2 to $1.5/MWh, depending on the particulate control device.
- Little or no detectable Hg was leached by the TCLP or SGLP procedures for any of the ash samples.

BACKGROUND

MERCURY EMISSIONS FROM COAL-FIRED POWER PLANTS

Mercury is an element that can be neither created nor destroyed. Therefore, any mercury contained in the coal is released when the coal is burned. The mercury forms various chemical species in the boiler depending on the coal characteristics and the boiler operating conditions. A portion of the mercury exits the boiler in the particulate form and is easily captured downstream in the ESP or fabric filter. However, the majority of the mercury will end up in the vapor phase in two forms: elemental mercury and oxidized mercury. The speciation of mercury is important because it affects both the control of mercury and the environmental impact of the emissions.

Elemental mercury, also referred to as mercury zero (Hg^0), is not water-soluble. Therefore, it cannot be captured in wet scrubbers. However, this same feature means that emissions of elemental mercury will not be likely to deposit in the environment near the plant. Oxidized mercury, also known as reactive mercury, ionic mercury, mercury chloride, and mercury plus two (Hg^{++}) is water-soluble. This means that it can be captured in wet scrubbers, but not necessarily fully retained due to subsequent reactions leading to some re-emission of elemental mercury.

During 1999, EPA conducted an Information Collection Request (ICR) program in which every sixth trainload of coal from every coal-fired plant in the U.S. was analyzed to determine the concentration of mercury and chloride. This program provided a great deal of information about the variability of these compounds in the various coals being burned to produce power in the U.S. (EPA Web site, ICR database, 2002). These data showed that there was not a great deal of difference in the concentrations of mercury in eastern bituminous and western subbituminous coals. Therefore, in contrast to the option of switching coals for SO_2 control, there will not be a similar motive to coal switch to meet a mercury regulation.

Chloride in the coal was also analyzed during the ICR program. Coal chloride content is a key parameter relative to mercury emissions and control. The chloride has two important impacts on mercury control. First, the amount of chloride can alter the speciation of mercury in the boiler. Coals with higher chloride are more likely to result in greater concentrations of the oxidized forms of mercury, where low-chloride coals will produce more elemental mercury. In addition, the concentration of gas-phase HCl in the flue gas is a direct result of the chloride in the coal. HCl has been shown to be a key parameter in the reaction between vapor-phase mercury species and solid sorbents.

Figure 2 shows the distribution of chloride content of various coal types. As can be seen, there is a significant difference between the chloride content of eastern and western coals. The western coals, both bituminous and subbituminous, have very low chloride levels with most having less than 100 ppm. The eastern bituminous coals have very high chloride levels, many with levels exceeding 1,000 ppm. Thus, when coal is burned, the speciation of

mercury in flue gas from western fuels favors the elemental form whereas the eastern coals have a higher concentration of the oxidized forms of mercury.

In addition to analyzing coal characteristics, the ICR program also provided data to estimate the amount of emissions from coal-fired boilers in the U.S. It was determined that each year, approximately 75 tons of mercury enters the plants with the coal. Of these 75 tons/yr, approximately 40%, or 27 tons/yr, is captured with existing control devices and ends up in the fly ash or scrubber sludge. The remaining 48 tons/yr of mercury is emitted from the stacks.

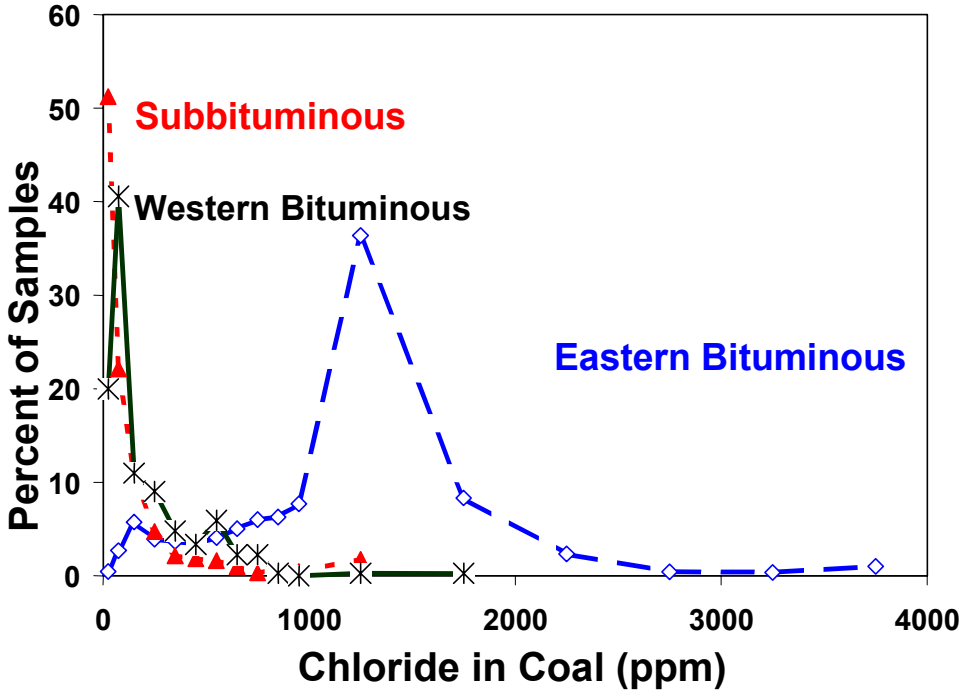

Figure 2. Distribution of Chloride Content as a Function of Coal Type.

MERCURY CONTROL BY EXISTING EQUIPMENT

Where Parts I and II of the ICR program were specific to coal measurements, Part III required stack gas mercury measurements at eighty-four different plants. The plants were selected for testing to provide enough data to cover a range of boiler designs, coal types, and air pollution control equipment (Kilgroe and Srivastava, 2001). These data provided mercury speciation in flue gas and the capture of mercury by existing air pollution control equipment.

These data showed that for every type of control device, mercury capture is higher for bituminous coals than for subbituminous coals. This is due to the higher levels of oxidized mercury generated from bituminous coals. Flue gas from subbituminous coals consists predominantly of elemental mercury, which is much more difficult to capture without

treatment. This is especially true for wet and dry scrubbers. The data also showed that fabric filters enhance the capture of mercury compared to ESPs. This is because the filter cake there provides intimate contact between the vapor-phase mercury and the solid materials such as fly ash and LOI carbon.

Tests have confirmed that wet and dry scrubbers, which are located on 25% of the power plants, can be effective for removing mercury from some coals. However, scrubbers are only effective at removing one form of mercury, water-soluble oxidized mercury, and cannot remove elemental mercury. Because of this limitation, mercury control with scrubbers varies from less than 10% removal to greater than 90% removal. They work best on bituminous coals with high chloride levels and they are quite ineffective on western subbituminous coals.

ACTIVATED CARBON INJECTION

Injecting a sorbent such as powdered activated carbon into the flue gas represents one of the simplest and most mature approaches to controlling mercury emissions from coal-fired boilers. The gas-phase mercury in the flue gas contacts the sorbent and attaches to its surfaces. The sorbent with the mercury attached is then collected by the existing particulate control device (PCD)—either an electrostatic precipitator or a fabric filter. This combined material, consisting of nominally 99% fly ash and 1% sorbent, is then either disposed of or beneficially used.

The most commonly used sorbent for mercury control has been activated carbon. For the past two decades, powdered activated carbon injection upstream of a fabric filter has been successfully used for removing mercury from flue gases from municipal and hazardous waste combustors. Activated carbon is carbon that has been “treated” to produce certain properties such as surface area, pore volume, and pore size. Activated carbon can be manufactured from a variety of sources, (e.g., lignite, peat, coal, wood). More commonly, steam is used for activation, which requires carbonization at high temperatures in an oxygen-lean environment. As some carbon atoms are vaporized, the desired highly porous activated carbon is produced. Commercially, activated carbons are available in a range of particle sizes, as well as other characteristics that are needed for a specific application.

The type of particulate control equipment is a key parameter that both defines the amount of sorbent that is required and provides the ultimate limitation of the amount of mercury that can be removed. When the sorbent is injected into the flue gas, it mixes with the gas and flows downstream. This provides an opportunity for the mercury in the gas to contact the sorbent where it is removed. This is call “in-flight” capture. The sorbent is then collected in the particulate control device where there is a second opportunity for sorbent to contact the mercury in the gas.

EQUIPMENT AND TEST PLAN

One of the most critical elements of the program was the field-testing, which relied upon accurate, rapid measurements of mercury concentration and a sorbent injection system that realistically represented commercially available technology.

MERCURY MEASUREMENTS

Near real-time vapor-phase mercury measurements were made using a semi-continuous emissions monitor (S-CEM) designed and operated by Apogee Scientific, Inc. This instrument was developed with EPRI funding to facilitate EPRI research and development efforts. Two analyzers were dedicated to the program. They were set up at the inlet and outlet of the particulate control device that was used to collect the activated carbon. The S-CEMs operated continuously throughout the testing periods, providing speciated, vapor-phase mercury concentrations.

A particulate-free sample was obtained by extracting flue gas using a heated, inertial filter. The sample then passed through a wet-chemical system to either convert all vapor-phase mercury species to elemental mercury or to remove the oxidized portion to measure only the elemental mercury fraction. The sample was then measured for mercury content by utilizing a cold vapor atomic absorption spectrometer (CVAAS) (Sjostrom, et al., 2002a). A schematic of this system can be seen in Figure 3. Because the particulate matter is not analyzed, these instruments measure only vapor-phase mercury.

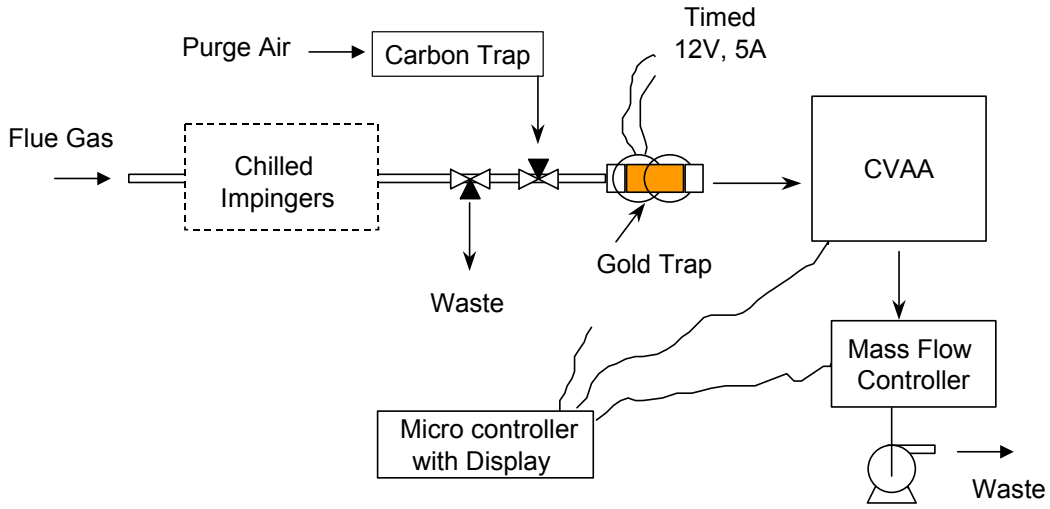

Figure 3. Process Sketch of Mercury Semi-Continuous Analyzer.

SORBENT INJECTION EQUIPMENT

Two different size sorbent injection systems were used on this program.

PortaPAC™ System

For Gaston and Salem Harbor, where lower sorbent feed rates were required, NORIT Americas, Inc., supplied a portable dilute-phase pneumatic injection system (PortaPAC™) that is typical of those used at municipal solid waste (MSW) facilities for mercury control with activated carbon. This system has a maximum feedrate of 300 lbs/hr. ADA-ES designed the sorbent distribution and injection components of the system.

Figure 4 is a picture of the PortaPAC™ when it was installed for use at Plant Gaston Unit 3B. Activated carbon delivered to the plant in 900-lb supersacks was loaded onto the skid by a hoist. The sorbent was metered by a variable speed screw feeder into an eductor that provided the motive force to carry the sorbent approximately 100 feet to the injection point.

Sorbent was pneumatically transported via flexible hose from the feeder to a distribution manifold at the injection level and injected into the flue gas through injection probes (three/duct). Figure 5 is a photograph of the distribution manifold used at all of the sites. Each manifold supplied up to six injectors. The injection system operated without plugging while injecting carbon-based products with D50 (mass median) particle size of 18 microns. The distribution system plugged once while feeding a finer material with a D50 of 6–7 microns.

Figure 4. Carbon Injection Skid Installed at Plant Gaston.

Figure 5. Distribution Manifold for Injection Lances at Plant Gaston.

Silo Injection System

At Pleasant Prairie and Brayton Point, a silo-based system was used. Since no previous full-scale test results were available, sorbent requirements for various levels of mercury control were predicted based on empirical models developed through EPRI funding (Durham, et al., 2002). The values used were based on an in-flight model with a one-second residence time and uniform sorbent size of 15 microns (size of commercially available PAC). Practical limits associated with bulk handling of sorbents, storage requirements, and increased loading to the ESP were also considered. Based on these assumptions, a silo system was designed to provide a maximum sorbent injection rate of 1,500 lbs/hr.

NORIT Americas fabricated the transportable sorbent injection system that consists of a bulk-storage silo and twin blower/feeder trains each rated at 750 lbs/hr. Sorbents are delivered in bulk pneumatic trucks and loaded into the silo, which is equipped with a bin vent bag filter. From the two discharge legs of the silo, the sorbent is metered by variable speed screw feeders into eductors that provide the motive force to carry the sorbent to the injection point. Regenerative blowers provide the conveying air. A programmable logic controller (PLC) system is used to control system operation and adjust injection rates. Figure 6 is a photograph of the sorbent silo and feed train installed at Pleasant Prairie. Flexible hoses carried the sorbent from the feeders to distribution manifolds located on the ESP inlet duct, feeding the injection probes.

SPRAY COOLING SYSTEM

EnviroCare International provided a spray cooling system, which was used to cool the flue gas temperature at Pleasant Prairie. The spray cooling system was comprised of a valve rack skid, air and water headers, and spray lances. Compressed air and supply water from the plant were provided to the valve rack skid where controls regulated the air and water to obtain proper flows and pressures at the spray lances. Since the volume and temperature of the gases varied across the ESP inlet duct, the spray cooling system was engineered with two control zones.

In preparation for the field test at Pleasant Prairie, the internal duct bracing within 40 feet downstream of the spray lances was removed. Feedback thermocouples were also located 40 feet downstream of the spray lances and were used to regulate water flow and air pressure to the spray lances to maintain a predetermined flue gas temperature setpoint. This particular spray cooling system was designed to maintain a temperature difference of 50ºF between the inlet and outlet thermocouples of the spray cooling system.

Figure 6. Carbon Injection Storage Silo and Feeder Trains Installed at PPPP.

TEST PLAN

At each site, sorbent injection for mercury control was implemented on full-scale particulate control equipment to obtain performance and operational data. Combustion byproduct samples were collected concurrently to determine the impact of the sorbents on waste disposal and byproduct reuse practices. The tests were conducted in three distinct phases:

1. Baseline testing,
2. Parametric testing, and
3. Long-Term testing.

Baseline measurements were conducted after the injection equipment was installed. During this phase, no sorbent was injected into the flue gas. Mercury concentrations in the flue gas were measured with S-CEMs and by the Ontario Hydro method. During the field tests, operating data and coal and ash samples were also collected.

A series of parametric tests was then conducted to determine the optimum sorbent and operating conditions that would be required for several levels of mercury control. Based on results from these tests, a two-week test under optimized conditions was conducted to assess longer-term impacts to the PCD, byproduct management practices, and auxiliary equipment operation. During the long-term tests, mercury removal efficiencies were measured by the S-CEMs and verified by Ontario Hydro method measurements.

FIELD TEST PROGRAMS

GASTON

The E.C. Gaston Electric Generating Plant, located in Wilsonville, Alabama, has four 270-MW balanced draft and one 880-MW forced draft coal-fired boilers. All units fire a variety of low-sulfur, washed, eastern bituminous coals. Gaston Unit 3 was chosen as the first test site because it allowed testing of a unique configuration for mercury control.

COHPAC® is an EPRI-patented concept that places a high air-to-cloth ratio baghouse downstream of an existing ESP to improve overall particulate collection efficiency. The process becomes TOXECON™ when a sorbent such as activated carbon is injected between the baghouse and ESP (Figure 7). With this configuration, the ash collected in the upstream ESP remains acceptable for sale (typically >99% of the ash.) The downstream baghouse provides an effective mechanism for the activated carbon to have intimate contact with vapor-phase mercury, resulting in high levels of mercury control at relatively low sorbent injection rates.

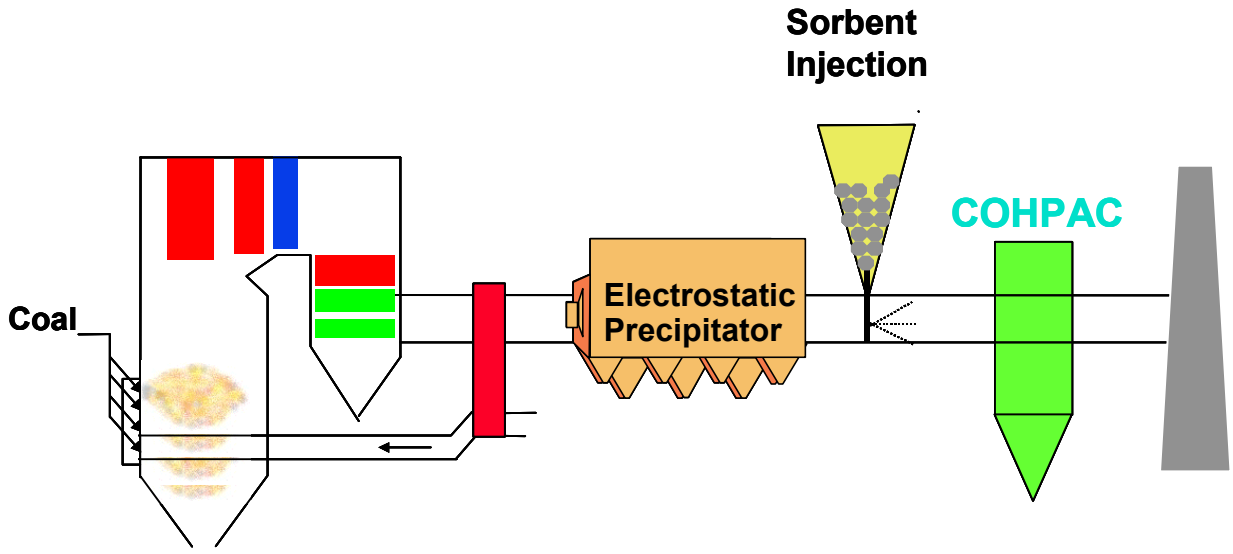

Figure 7. Configuration Combining ACI and a Secondary Fabric Filter.

The advantages of the TOXECON™ and COHPAC® configurations are:

- Sorbents are mixed with only a small fraction of the ash (nominally 1%), which reduces the impact on ash reuse and waste disposal.
- Full-scale field tests have confirmed that fabric filters require only 10–20% of the sorbent required by ESPs to achieve similar mercury removal efficiencies.
- Capital costs for COHPAC® are less than other options such as replacing the ESP with a full-sized baghouse or larger ESP.

- COHPAC® requires much less physical space than either a larger ESP or full-size baghouse system.
- Outage time can be significantly reduced with COHPAC® systems in comparison to major ESP rebuilds/upgrades.

Site Description

The primary particulate control equipment on all Gaston units are hot-side ESPs. Units 1 and 2, and Units 3 and 4 share common stacks. In 1996, Alabama Power contracted with Hamon Research-Cottrell to install COHPAC® downstream of the hot-side ESP on Unit 3. This COHPAC® system was designed to maintain Unit 3 and 4's stack opacity levels below 5% on a 6-minute average (Miller et al., 1999)

The COHPAC® system at Gaston is a hybrid pulse-jet type fabric filter, designed to treat flue gas volumes of 1,070,000 acfm at 290ºF (gross air-to-cloth ratio of 8.5 ft/min with on-line cleaning). The COHPAC® fabric filter consists of four (4) isolatable compartments, two compartments per air-preheater identified as either A- or B-side. Each compartment consists of two bag bundles, each having a total of 544 23-foot long, polyphenylene sulfide (PPS) felt filter bags, 18 oz/yd^2 nominal weight. This results in a total of 1,088 bags per compartment, or 2,176 bags per casing (Miller et al., 1999). The testing was conducted on one-half of the gas stream, nominally 135 MW. The side chosen for testing was B-side. A-side was monitored as the control unit.

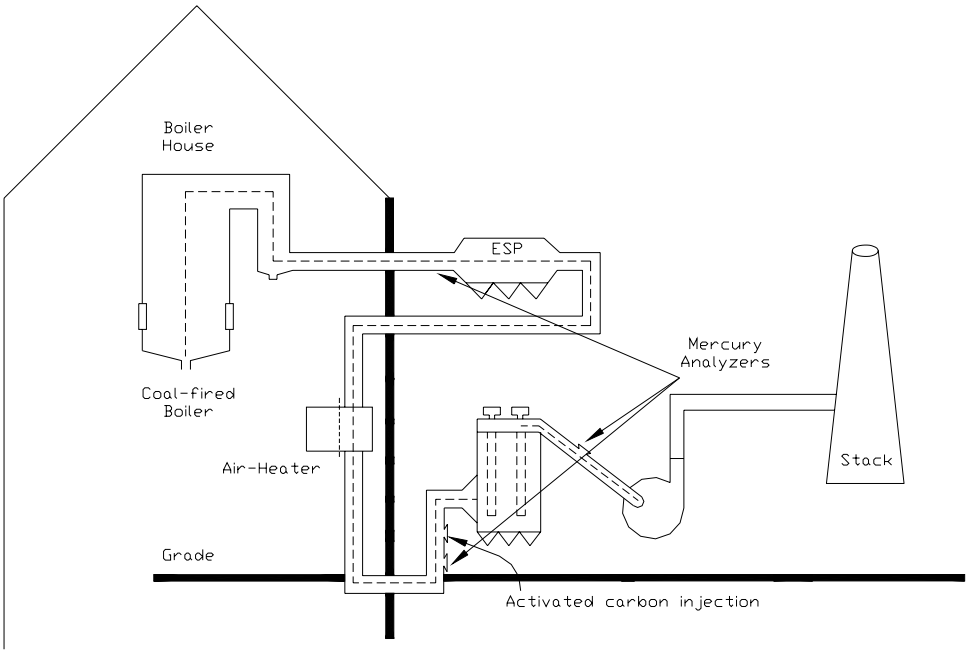

Figure 8. Flow Schematic of Gaston Unit 3, Showing Injection and Measurement Locations.

The hot-side ESP is a Research-Cottrell weighted wire design. The specific collection area (SCA) is 274 ft^2/1,000 acfm. Depending on the operating condition of the hot-side ESP, nominally 97–99+% of the fly ash is collected in the ESP. The remaining fly ash is collected in the COHPAC® system. The average inlet particulate mass concentration into COHPAC® between 1/97 and 4/99 was 0.0413 gr/acf (Miller et al., 1999). Hopper ash from both the ESP and baghouse are sent to a wet ash pond for disposal. A hydrovactor system delivers the fly ash to the pond.

Figure 8 shows a diagram of the location of the various components of the air pollution control train. Design parameters for Gaston Unit 3 are presented in Table 2. For the mercury control program, carbon-based dry sorbents were injected upstream of COHPAC®, downstream of the ESP over an eight-week period.

Table 2. Site Description Summary, Gaston Unit 3.

Parameter Identification	Description
Process	
Boiler Manufacturer	B&W Wall-Fired
Burner Type	B&W XCL
Low-NO_x Burners	Yes
NO_x Control (Post Combustion)	None
Temperature (APH Outlet)	290ºF
Coal (Typical; this unit fires a variety of coals)	
Type	Eastern Bituminous
Heating Value (Btu/lb)	13,744
Moisture (%)	6.9
Sulfur (%)	0.9
Ash (%)	13.1
Hg (μg/g)	0.06
Cl (%)	0.03
Control Device	
Type	Hot-Side ESP with COHPAC®
ESP	
Manufacturer	Hamon Research-Cottrell
Design	Weighted Wire
Specific Collection Area (ft^2/1,000 afcm)	274
Flue Gas Conditioning	None
Baghouse Manufacturer	Hamon Research-Cottrell
Design	Pulse-Jet, Low Pressure–High Volume
Air-to-Cloth Ratio (acfm/ft^2)	8.5:1 (gross), On-Line Cleaning

Test Results

Baseline Tests

The first field measurements were made prior to installing the injection equipment. The objectives for the pre-baseline tests were to:

1. Document mercury emissions across COHPAC®; and
2. Perform screening tests for mercury adsorption characteristics of several activated carbons that were candidate sorbents for the full-scale tests.

Table 3 presents vapor-phase mercury measurements during the pre-baseline tests in January 2001 on Unit 3. Two analyzers were used for these tests. The analyzers were set up to measure simultaneously either across the hot-side ESP or COHPAC®

The results show that vapor-phase mercury varied between 7 and 10 μg/dNm^3 at all three locations. There was no measurable removal of vapor-phase mercury across either the hot-side ESP or COHPAC®.

Table 3. Pre-Baseline Mercury Measurement Results (S-CEM).

Location	Total Mercury μg/dNm^3 @ 3% O_2	Oxidized Mercury %
ESP Inlet	7–10	5–33
ESP Outlet/COHPAC® Inlet	7–10	29–51
COHPAC® Outlet	7–10	52–76
Mercury Removal Across ESP	0%	
Mercury Removal Across COHPAC®	0%	

These results are comparable to those made during ICR measurements on Unit 1 for total mercury concentrations and removal efficiencies. ICR measurements showed total mercury concentrations between 6.0 and 7.5 μg/dNm^3 and no mercury removal across the hot-side ESP (Sjostrom, et al., 2002a).

No mercury removal was measured across COHPAC® without the addition of sorbents. Review of data collected through the ICR at other plants shows that there was significant natural mercury capture on units with conventional-type baghouses when firing bituminous coals (Sjostrom, et al., 2002a). This natural collection is assumed to occur because of exposure of the flue gas to ash on the bag dustcake. The ash at Gaston was tested for mercury adsorption capacity by URS Corporation. Analysis of the ash showed high carbon content throughout the total size distribution and an adsorption capacity that was reasonable when compared to other ashes. However, since COHPAC® is downstream of the hot-side ESP and the ESP was in excellent condition at the time of the tests, the inlet loading to COHPAC® was very low (0.04 gr/acf on average and less than 0.01 gr/acf during the tests), so there was a relatively small amount of ash present on the bags to react with the mercury.

The portion of vapor-phase mercury in the oxidized state increased in the direction of flow. There was a greater percentage of elemental mercury at the hot-side inlet (economizer outlet) than there was at either the COHPAC® inlet or outlet. The most significant oxidation occurred across the COHPAC® baghouse. Similar phenomena have been documented in EPRI tests across baghouses with fiberglass and PPS fabric bags.

After equipment installation and checkout, a set of baseline tests was conducted immediately prior to the first parametric test series to document current operating conditions. During this test, boiler load was held steady at "full-load" conditions during testing hours, nominally 7:00 a.m. to 7:00 p.m. Mercury across B-side of COHPAC® was measured using two separate methods:

1. S-CEMs, and
2. Modified Ontario Hydro Method.

In addition to monitoring mercury removal, it was important to document the performance of COHPAC® during sorbent injection. The primary COHPAC® performance indicator at this site was cleaning frequency. Pressure drop is controlled by the cleaning frequency. It was expected that cleaning frequency would increase with the increased particulate loading from sorbent injection. Cleaning frequency was monitored before, during, and after sorbent injection.

Results from the Ontario Hydro tests conducted by Southern Research Institute are presented in Table 4. Similar to pre-baseline measurements, there was no measurable mercury removal across COHPAC®. The average of the inlet and outlet total mercury measurements was about 15 μg/dncm. Coal analyses showed mercury levels in the three coal samples varied between 0.06 and 0.17 μg/g. Since Gaston burns coals from several different coal sources each day, it is difficult to correlate mercury level in the coal to a specific flue gas measurement; however, the higher coal mercury values correlate well with mercury measured in the flue gas.

Similar to the S-CEM results, the Ontario Hydro measurements also showed oxidation across COHPAC®. At the inlet, the average fraction of oxidized mercury was 61%, and increased to 77% at the outlet. Flue gas temperatures during these tests were nominally 255ºF.

Table 4. Baseline Ontario Hydro Measurements at COHPAC® Inlet and Outlet.

Location	Particulate (μg/dncm)[1]	Elemental (μg/dncm)[1]	Oxidized (μg/dncm)[1]	Total (μg/dncm)[1]	Total (lbs/TBtu)
COHPAC® Inlet	0.09	5.97	9.54	15.6	11.4
COHPAC® Outlet	0.01	3.34	11.19	14.54	10.6
Average RE %	**88.9**	**44.0**	**-17.3**	**6.8**	
% of Total at Inlet	0.5	38.3	61.2		
% of Total at Outlet	0	11.9	76.9		

Note 1: Normal: T = 32 ºF, Values corrected to 3% O_2

Parametric Tests

A series of parametric tests was conducted to determine the optimum operating conditions for several levels of mercury control up to 90% mercury removal, for several activated carbon products. NORIT Americas' lignite-based PAC, DARCO FGD, was chosen as the benchmark sorbent. Sorbent type and injection concentration for the long-term tests were chosen based on results from these tests.

In all, 15 different parametric conditions were tested. The primary variables were carbon type and target mercury removal level. Other variables included COHPAC® cleaning settings and flow through the baghouse. Although lower flue gas temperatures have been correlated with increased mercury removal, temperature was not a variable during these tests because normal operating temperatures at this plant were between 250ºF and 270ºF, which is cool enough for acceptable removal. A summary of the parametric test conditions is presented in Table 5. Unless noted, all tests were conducted with the boiler at full-load conditions and COHPAC® cleaning at a drag (drag = pressure drop/air-to-cloth ratio) initiate setpoint of 0.6 inches H_2O/ft/min. A description of the different carbons used in these tests is presented in Table 6.

Table 5. Summary of Parametric Test Conditions.

Test Series	Carbon Name	Target Hg Removal Efficiency (%)	Non-Standard Conditions
1–5	DARCO FGD	50, 75, and 90	Standard
6–9	NORIT PAC2B	50, 75, and 90	Standard
10	None	Baseline	Standard
11	DARCO Insul	90	Standard
12	HydroDARCO-C	90	Standard
13 a–c	DARCO FGD	75	Change to pressure drop initiate clean
14	DARCO FGD	50	Lower A/C to 4 ft/min
15	DARCO FGD	50	Compare to test 14 with A/C = 7 ft/min

Table 6. Description of NORIT Carbons used in Parametric Tests.

Name	Description	Particle Size Distribution[a]		
		D95	D50	D5
DARCO FGD	Lignite activated carbon	52	15–20	<3
NORIT PAC2B	Subbituminous/bituminous blend activated carbon	52	15–20	<3
DARCO Insul	Fine chemically washed specialty product	25	6–7	<2
HydroDARCO-C	Coarser FGD	100	30	3

Note a: Percent of particles less than size in microns

The parametric testing phase was used to measure mercury removal as a function of injection concentration and sorbent type, and evaluate the impact of sorbent injection on COHPAC® performance. Feedback from the S-CEMs were invaluable in making timely, real-time decisions on test conditions. Examples of the data provided from the S-CEMs are presented in Figure 9. These data are from the first week of parametric tests with DARCO FGD, test numbers 1–5. Reduction in outlet mercury concentration can be seen to correlate with injection concentration.

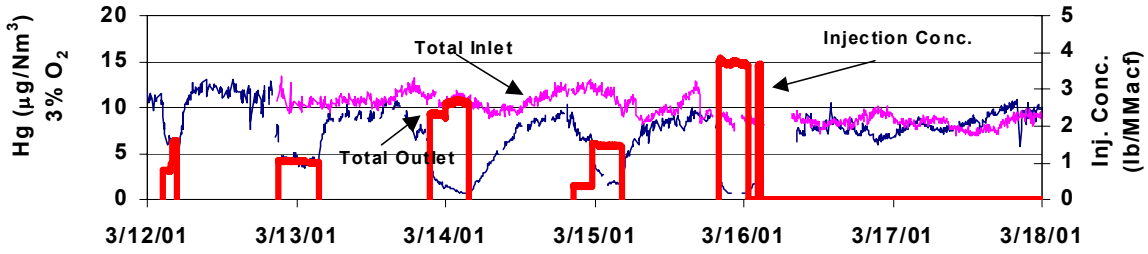

Figure 9. S-CEM Mercury Measurements during the First Week of Parametric Tests with NORIT DARCO FGD PAC.

Figure 10 presents mercury removal efficiencies as activated carbon injection concentrations were varied during the parametric tests for several activated carbons (see Table 5 and Table 6 for description of test conditions). This figure shows that mercury removal increased nearly linearly with injection rate up to 2 lbs/MMacf and then leveled off at about 90% removal with higher injection providing no additional benefit. This figure also shows that there was no measurable performance difference between the different activated carbons.

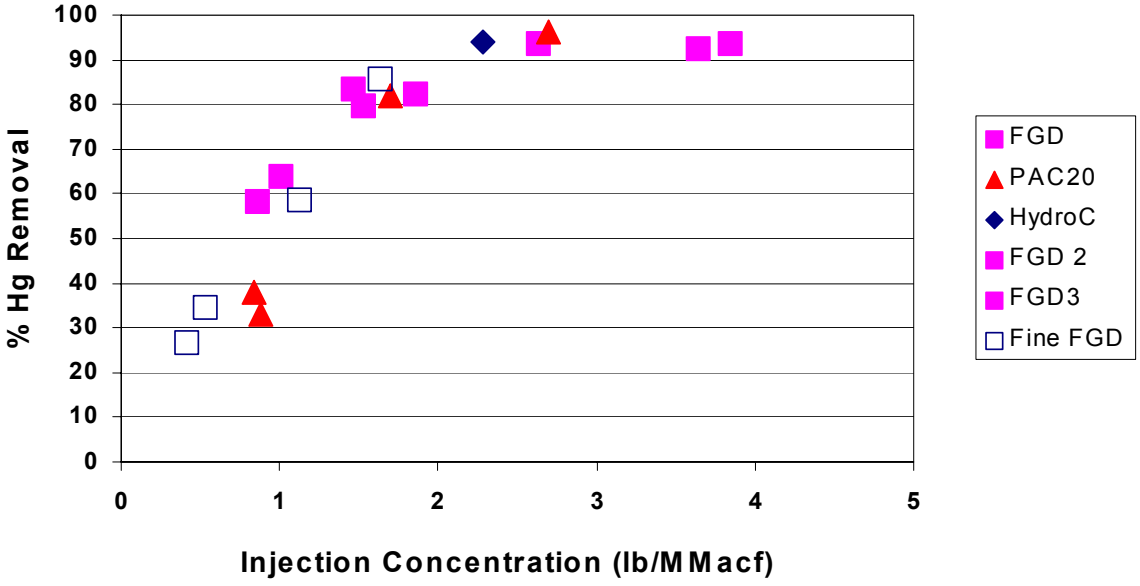

Figure 10. Mercury Removal Trends across COHPAC® as a Function of PAC Injection Concentrations. Measurements made during Parametric Tests, March 2001.

Carbon injection significantly increased the cleaning frequency of the COHPAC® baghouse. Figure 11 presents actual cleaning frequencies that were measured as a function of different carbon injection concentrations. At an injection concentration of 2.0 lbs/MMacf, the cleaning frequency increased from 0.5 to 2 pulses/bag/hour, or by a factor of 4. An acceptable cleaning frequency at this site was determined to be 1.5 pulses/bag/hour, to maintain long-term bag life.

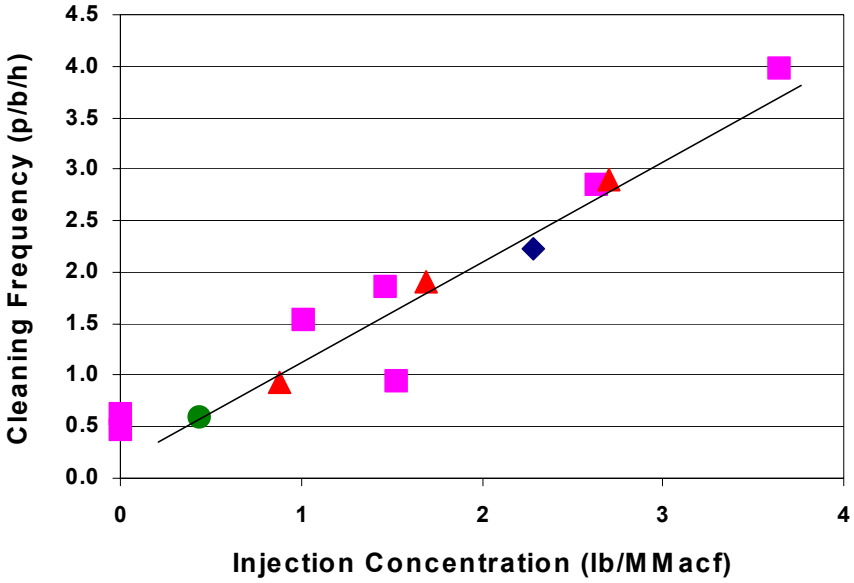

Figure 11. COHPAC® Cleaning Frequency in Pulses/Bag/Hour as a Function of PAC Injection Concentration. Measurements made during Parametric Tests, March 2001.

Long-Term Tests

Long-term testing at "optimum" plant operating conditions, as determined from the parametric tests, was planned to gather data on:

- Mercury removal efficiency over time;
- The effects of sorbent injection on COHPAC® and balance-of-plant equipment; and
- Operation of the injection equipment to determine the viability and economics of the process.

During these tests, carbon was injected continuously 24 hours per day, for 9 days. Based on results from the parametric tests, DARCO FGD activated carbon was chosen as the sorbent for these tests. Injection rate was determined taking into consideration both mercury removal and the projected increase in COHPAC® cleaning frequency. An injection concentration of 1.5 lbs/MMacf was chosen to maintain COHPAC® cleaning frequency below 1.5 pulses/ bag/hour.

Similar to the baseline test series, mercury was measured by both the S-CEMs and the Ontario Hydro method. COHPAC® performance, coal and ash samples, and plant CEM data were collected. During these tests an EPA audit of the manual measurements was performed.

The long-term tests started on April 18, 2001, and carbon was injected continuously until April 26. For the first five days, full-load boiler conditions were held between the times of 0700 and 2000, with load following at other times. During the three days when the Ontario Hydro tests were conducted, full load was maintained 24 hours/day. At the beginning of the tests, time was needed to work out a COHPAC® cleaning logic issue and there was a short period when load was lowered to fix a mill problem. The final seven days of the test were conducted at the optimized PAC feedrate and COHPAC® cleaning logic.

Three sets of Ontario Hydro measurements were made at three locations: 1) the inlet of the hot-side ESP, 2) the COHPAC® inlet, and 3) the COHPAC® outlet. Southern Research Institute conducted tests across COHPAC® and ARCADIS G&M, Inc., made the measurements upstream of the hot-side ESP. The hot-side measurements were made using an experimental in-duct, quartz thimble to minimize sampling artifacts often seen with this method. Artifacts have been known to occur when the particulate collected on the filter captures vapor-phase mercury, resulting in higher particulate-phase mercury than is really present. Sampling artifacts from particulate on the filter were not as much of a concern at the other two locations because most of the particulate was already removed by either the hot-side ESP or COHPAC®

Table 7 presents average, speciated mercury removal across COHPAC®. These data show that the inlet to the hot-side ESP and the inlet to COHPAC® have similar, average mercury concentrations and speciation, and that mercury is oxidized across COHPAC®. The outlet mercury concentrations show the effect of carbon injection with overall low mercury emissions for all species. The overall average reduction in total mercury is 90%. At the outlet the predominate species of mercury is the oxidized form; however, it is still 85% less than what was present upstream of PAC injection.

Figure 12 presents inlet and outlet mercury concentrations as measured by the S-CEMs, boiler load, and PAC injection concentration during the last five days of the long-term test. Periods when Ontario Hydro measurements were made are also identified. The S-CEMs indicate that mercury removal was nominally 87, 90, and 88% during the Ontario Hydro tests. This correlates well with the manual measurements. However, it is important to note that the S-CEMs showed that the average mercury removal efficiency over the multi-day time period was 78%, with variations between 36% to over 90%. This difference is probably due to varying coal and operating conditions over time. Figure 12 also shows that during this five-day period, inlet mercury concentration varied by nearly a factor of five. Outlet concentrations can be seen to follow the inlet and there are times during these transitional periods when removal efficiencies are fairly low. During the period when the Ontario Hydro tests were run, inlet mercury levels were low and fairly steady. These tests were conducted under ideal conditions and may show the best-case condition for mercury control at this injection rate.

During the test program, sorbent was injected at a constant rate with no attempt to increase sorbent when the inlet mercury concentration increased. However, the data in Figure 12 highlight the importance of having S-CEMs to use as process control for a permanent mercury control system.

Table 7. Average Mercury Removal Efficiencies across COHPAC® as Measured with Ontario Hydro Method during Long-Term Tests.

Location	Particulate (µg/dncm)[1]	Elemental (µg/dncm)[1]	Oxidized (µg/dncm)[1]	Total (µg/dncm)[1]	Total (lbs/TBtu)
COHPAC® Inlet	0.23	6.37	4.59	11.2	8.2
COHPAC® Outlet	0.12	0.91	0.03	1.1	0.8
Average RE %	**45.6**	**85.7**	**99.3**	**90.6**	

Note 1: Normal: T = 32 °F, Values corrected to 3% O_2

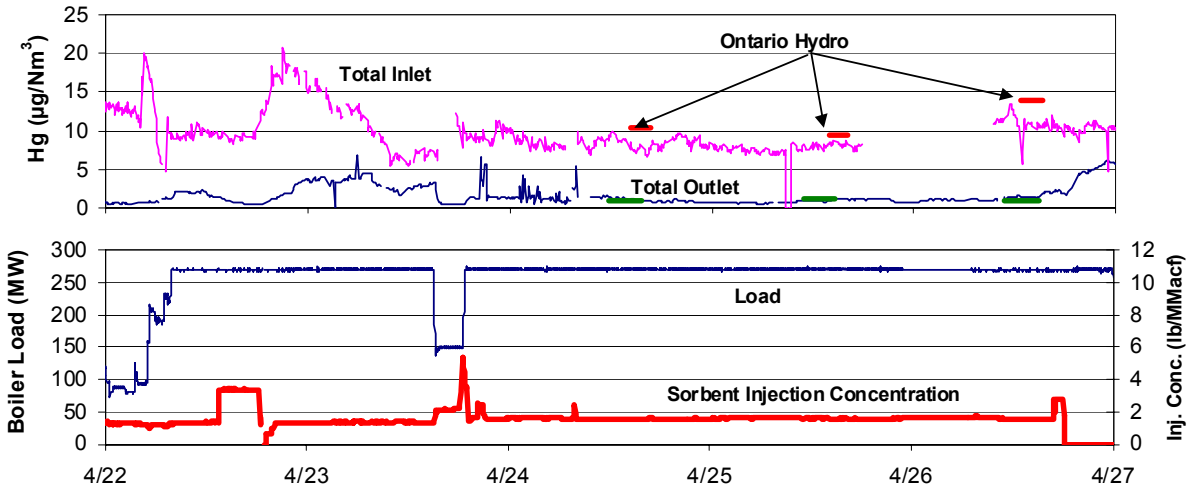

Figure 12. Inlet and Outlet COHPAC® Mercury Concentrations, Boiler Load, and PAC Injection Concentration during Long-Term Tests, April 2001.

The most challenging time for COHPAC® performance was during the period with continuous full-load operation and PAC injection. The cumulative cleaning frequency increased to a high of 1.3 pulses/bag/hour, but was mostly maintained at levels less than 1.0 pulses/bag/ hour.

Conclusions

A full-scale evaluation of mercury control using activated carbon injection upstream of a COHPAC® baghouse was conducted at Alabama Power Company's Plant Gaston Unit 3. Results and trends from these relatively short-term tests were encouraging. The overall test conclusions are:

- Effective mercury removal, up to 90% efficiency, was obtained for short operating periods (eight hours) by injecting powdered activated carbon upstream of COHPAC®.
- A significant increase in the cleaning frequency of the COHPAC® baghouse occurred with the injection of activated carbons. At this site, the maximum acceptable cleaning frequency and pressure drop limited the amount of sorbent that could be injected and therefore the maximum mercury removal actually achievable. Based on these results, it will be necessary to take into consideration the sorbent injection rate in the design of future COHPAC® baghouses and perhaps design the baghouses more conservatively.
- On average, around 78% mercury removal was obtained when PAC was injected into COHPAC® 24 hr/day during long-term tests. Mercury removal varied throughout the period and ranged from 36% to 90%.
- To verify S-CEM measurements during the long-term tests, mercury removal across COHPAC® was measured following the Ontario Hydro method. Results showed an average 90% removal for the three tests periods. These results confirmed the high mercury removal measured with the S-CEMs.
- Additional testing over longer periods (up to a year) need to occur to determine the impact of carbon injection on bag life (pressure drop and bag strength) and outlet particulate emissions.

PLEASANT PRAIRIE

The second test was conducted at Wisconsin Electric's Pleasant Prairie Power Plant (PPPP) Unit 2. This site was of key interest because it was the only plant included in the NETL program that burns western, low-sulfur subbituminous coal. The particulate control device was a cold-side ESP, which represents the control device of choice at over 90% of nation's coal-fired boilers. Other features of this test site included:

- The ability to isolate one ESP chamber (one-fourth of the unit, approximately 150 MW);
- The challenge of implementing mercury control at a site where baseline mercury measurements (1999) showed no significant native mercury removal and a flue gas mercury dominated by the elemental species;
- A duct configuration with long, unobstructed runs that allowed adequate space for the installation of water injection lances upstream of the sorbent injection lances so that the effects of spray cooling (to achieve lower flue gas lower temperatures) on mercury control could be evaluated; and
- A keen interest in the impact of activated carbon on fly ash sold for use in concrete.

Site Description

Wisconsin Electric Power Company, a subsidiary of Wisconsin Energy Corporation, owns and operates Pleasant Prairie Power Plant located near Kenosha, Wisconsin. The plant has two (2) 600-MW balanced-draft coal-fired boilers. Unit 2 was chosen as the test unit. The units fire a variety of Powder River Basin (PRB) low sulfur, subbituminous coals.

The primary particulate control equipment consists of cold-side ESPs of weighted wire design and liquid sulfur trioxide (SO_3) flue gas conditioning. The precipitators were designed and built by Research-Cottrell and the flue gas conditioning system was supplied by Wahlco, Inc. The system was originally designed to collect fly ash from the Riley Stoker turbo-fired boiler with design superheated steam conditions of 1,990 psig/995ºF. The boiler was designed to burn low-sulfur coal at a gross nominal generating capacity of 617 MW (580 MW net). The design flue gas flow was 2,610,000 acfm at 280ºF. The design collection efficiency was 99.72%. There is a common stack supporting two sister units.

Unit 2 ESP was commissioned and put into service in 1985. The equipment consists of four (4) electrostatic precipitators that are arranged piggyback style and designated 2-1, 2-2, 2-3, and 2-4. Each of the four precipitators is two (2) chambers wide and four (4) mechanical fields deep with eight (8) electrical fields in the direction of gas flow. The specific collection area (SCA) is 468 ft^2/1,000 acfm. The unit employs sixty-four (64) transformer/rectifiers (T/Rs), sixteen (16) on each precipitator. The T/Rs are capable of double half-wave or full-wave operation. At this time, the T/Rs are in full-wave operation.

Hopper ash is combined from all four precipitators in the dry ash-pull system. The ash is sold as a cement powder substitute in concrete and is considered a valuable byproduct. One precipitator's ash can be isolated from the balance of the unit.

A summary of important descriptive parameters for Pleasant Prairie Unit 2 is presented in Table 8.

Table 8. Site Description Summary, Pleasant Prairie Unit 2.

Parameter Identification	Description
Process	
Boiler Manufacturer	Riley Stoker Turbo-Fired
Burner Type	Riley Stoker Direction Flame
Low NO_x Burners	No
Steam Coils	No (glycol preheater)
Over Fire Air	No
NO_x Control (Post Combustion)	None
Temperature (APH Outlet)	280ºF
Coal (Typical)	
Type	Powder River Basin
Heating Value (Btu/lb)	8,400
Moisture (%)	20.1
Sulfur (%)	0.43
Ash (%)	7.5
Hg (µg/g)	0.1
Cl (%)	0.0015
Control Device	
Type	Cold-Side ESP
ESP	
Manufacturer	Hamon Research-Cottrell
Design	Weighted Wire
Specific Collection Area (ft^2/1,000 afcm)	468
Flue Gas Conditioning	Wahlco SO_3 Injection

Figure 13 shows an isometric view of the Unit 1 ESPs at PPPP. Unit 2 is identical to Unit 1. One of the four ESPs was treated for mercury control, representing nominally 150 MW of the unit's total capacity. This met DOE's requirement to evaluate units no larger than 150 MW and also provided the opportunity to compare ESP performance and mercury removal on

parallel ESPs, one treated with sorbent injection and one untreated. The injection tests were conducted across the 2-4 ESP.

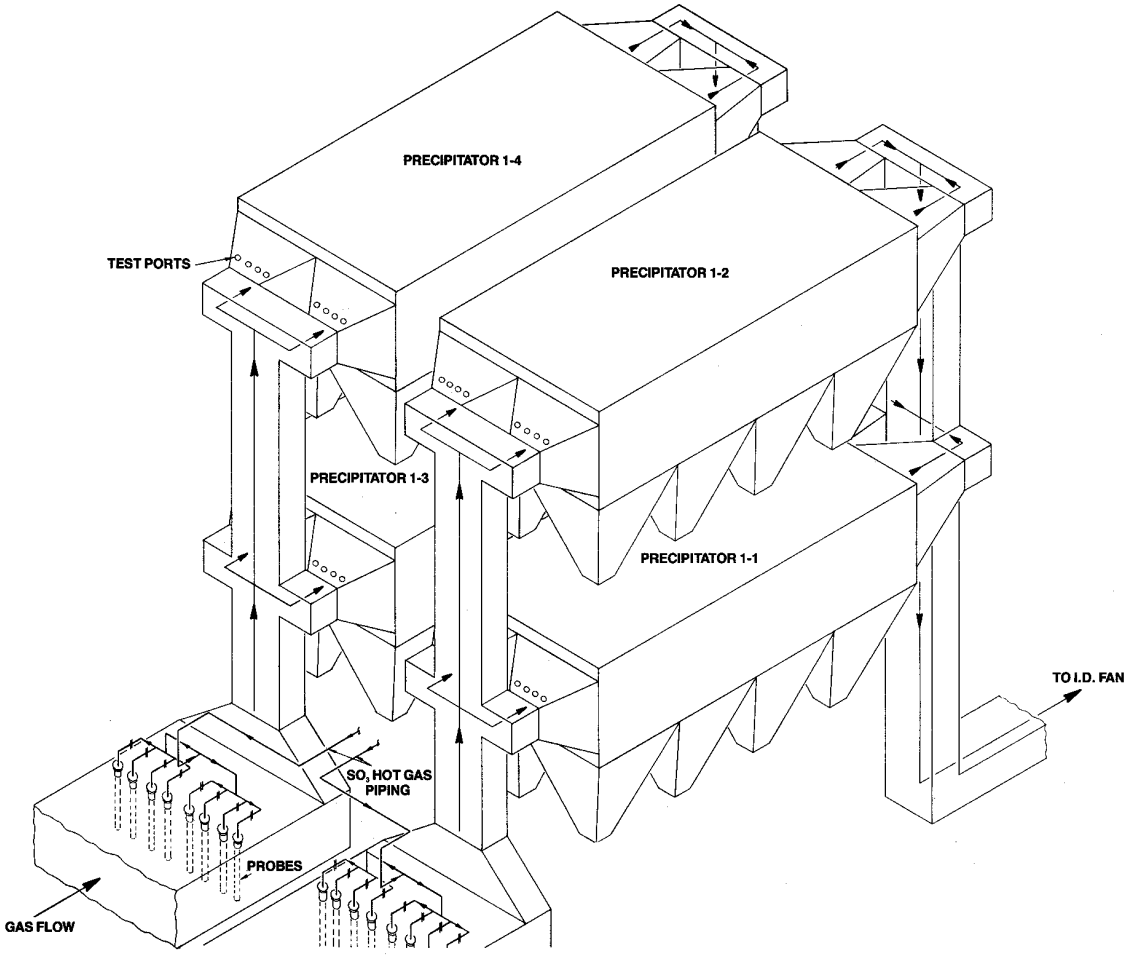

Figure 13. Isometric View of Precipitator Arrangement at Pleasant Prairie.

The 2-4 ESP is the top box of the piggyback configuration and therefore had a long duct run which could accommodate both sorbent injection and spray cooling, and still have adequate residence time for both.

Sorbent for mercury control was injected into the ductwork upstream of the ESP and downstream of the SO_3 injection grid. The sorbent had approximately 0.75 seconds of residence time in the duct before entering the ESP.

Test Results

Baseline Tests

After equipment installation and checkout, a set of baseline tests was conducted. During this test, boiler load was held steady at "full-load" conditions during testing hours, nominally 7:00 a.m. to 7:00 p.m. Both the S-CEMs and the modified Ontario Hydro method were used to measure mercury across the 2-4 ESP.

Results from Ontario Hydro tests conducted by GE Mostardi Platt in September 2001 are presented in Table 9. The average flue gas temperature during this period was 290ºF. The data show minimal baseline mercury removal across the ESP. The predominant species of mercury, whether at the inlet or outlet of the ESP, was elemental. Similar to measurements conducted at Gaston, there was oxidation of mercury in the direction of flow, in this case, across the ESP.

Table 9. Speciated Mercury Measured by Ontario Hydro Method, Baseline Conditions.

Location	Particulate (μg/dncm)[1]	Elemental (μg/dncm)[1]	Oxidized (μg/dncm)[1]	Total (μg/dncm)[1]	Total (lbs/TBtu)
ESP Inlet	1.97	12.22	2.51	16.7	12.2
ESP Outlet	0.01	9.80	6.01	15.8	11.5
Average RE %	**99.5**	**19.8**	**-139.3**	**5.3**	
% of Total at Inlet	11.8	73.1	15.0		
% of Total at Outlet	0	61.9	38.0		

Note 1: Normal: T = 32 ºF, Values corrected to 3% O_2

Coal samples collected during baseline tests and analyzed for mercury levels showed an average concentration of 0.099 μg/g. At PPPP a coal mercury level of 0.099 μg/g is equivalent to a mercury concentration of about 13.7 μg/dncm @ 3% O_2 in the flue gas.

Parametric Tests

Sorbents for the full-scale evaluation were selected based on several factors, including results from fixed-bed screening tests for mercury adsorption capacity, price, and availability of bulk delivered sorbent at quantities up to 100,000 lbs. NORIT Americas' lignite-based PAC, DARCO FGD, was chosen as the benchmark sorbent. Three additional sorbents were selected for full-scale evaluation in the parametric test series. The alternative sorbents were chosen because they had potential advantages over the benchmark sorbent. Two sorbents had smaller size distributions, which according to theory should significantly improve mercury collection efficiency. The third sorbent was a lower-capacity, lower-cost PAC. A description of the four sorbents selected for the parametric test is presented in Table 10.

Table 10. Description of Activated Carbons Selected for the Parametric Tests.

Name	Description	Particle Size Distribution[a]		
		D95	D50	D5
DARCO FGD	Lignite activated carbon	52	18	<3
DARCO FGL	Lignite activated carbon	52	18	<3
DARCO Insul	Fine, chemically washed specialty product	25	6–7	<2
Ground FGD	Lignite activated carbon	50	14	<3

Note a: Percent of particles less than size in microns

A series of parametric tests was conducted to determine the optimum operating conditions for several levels of mercury control. Primary variables were injection concentration, carbon type, SO_3 flue gas conditioning on/off, and spray cooling to 250ºF. In all, 16 different parametric conditions were tested. A summary of the parametric test conditions is presented in Table 11. Standard conditions were with the boiler at full-load operation, SO_3 conditioning on, and no spray cooling. Each test was run for a minimum of six hours, except for Test Series 13–16 where the small particle size distribution of the Insul sorbent caused feed problems.

Table 11. Summary of Parametric Test Conditions.

Test Series	Carbon Name	Target Injection Concentration (lbs/MMacf)	Non-Standard Conditions
1	DARCO FGD	10	SO_3 Conditioning Off
2, 3, 5	DARCO FGD	10, 20, 30	Standard
4	DARCO FGD	10	Spray Cooling to 250ºF
6, 8, 9, 10	Ground FGD	1, 2, 5, 10	Standard
7	Ground FGD	10	SO_3 Conditioning Off
11–12	FGL	5 and 10	Standard
13–16	Insul	0.5, 1, 2, 3	Standard

Mercury removal was monitored as a function of the sorbent injection concentration. In addition, the impact of sorbent injection on the performance of the ESP was monitored. An example of the data from the S-CEMs during the first week of parametric testing is presented in Figure 14. These five tests were conducted with DARCO FGD. SO_3 conditioning was off on September 24 and spray cooling was evaluated on September 27. Reduction and recovery of outlet mercury concentration can be seen to correlate with periods of sorbent injection. Inlet mercury levels varied between nominally 9 and 13 μg/dncm. During sorbent injection, outlet mercury concentrations decreased to a minimum of about 4 μg/dncm. In most cases the outlet mercury levels recovered to baseline levels within 10–12 hours after sorbent injection was stopped.

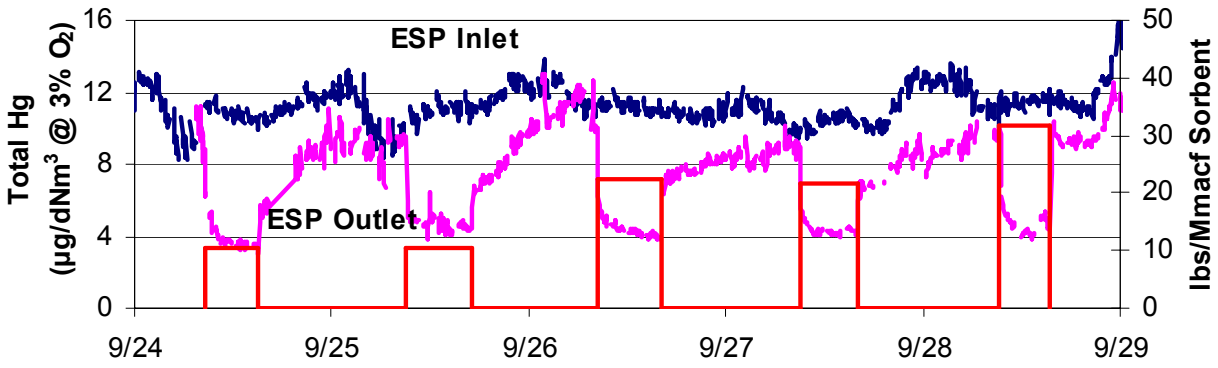

Figure 14. S-CEM Mercury Measurements during the First Week of Parametric Tests; September 2001.

The early tests showed a couple of surprising trends. First, the mercury removal efficiencies were significantly higher than expected at the lower injection concentrations. A model (Durham, et al., 2002) predicted about 20% in-flight removal at a sorbent injection rate of 10 lb/MMacf. An actual mercury removal rate of between 60 and 65% was measured at the 10 lb/MMacf test conditions. The in-flight model did not take into account mercury removal due to sorbent being deposited on internal structures, such as turning vanes, or on the ESP plates. It appears that the contribution from the carbon on the plates and other structures in the ESP to overall mercury removal was significant. The second unexpected trend was that mercury removal efficiencies did not increase to greater than nominally 60% at higher injection concentrations of 20 and 30 lbs/MMacf.

Spray Cooling Test

The first week of testing also included an evaluation of spray cooling. Flue gas temperature entering the 2-4 ESP deviated from north to south by nominally 40ºF, based on air heater rotation. The north side average temperature was about 300ºF at the start of the spray cooling test. Water was injected so that the average temperature 40 ft downstream of the water injection lances, as measured by the thermocouple array, was 260ºF, or a 40ºF decrease on the north side and a 20ºF decrease on the south side. When no enhancement of mercury removal was seen after several hours, the injection rate was increased to obtain a flue gas temperature of 250ºF. To achieve this level of cooling, 18 gpm of water was being injected. Because of the pozzolanic nature of the PRB ash, the internal ductwork and the sorbent injection lances (40 ft downstream of the spray lances) were monitored closely for ash deposition with an in-duct camera and by manual inspection of the sorbent lances. No sign of deposition was seen at 260ºF. However, after less than 50 minutes of cooling to 250ºF, deposition was building on the sorbent lances on the north side. No improvement in mercury removal was measured at these lower temperatures and because deposition was noted, the spray cooling test was terminated.

These results were not surprising because similar trends have been seen during slipstream testing by EPRI on PRB coal-derived flue gases. Based on work at other coal-fired units, lower temperatures increase the adsorption capacity of most sorbents. However, PAC adsorption capacities are already much higher than the threshold capacity needed for effective mercury removal. Increasing the capacity via flue gas cooling did not result in increased removal efficiency. However, operating in the ideal temperature range is still an important concept as it relates to the control of mercury. There are conditions where cooler temperatures may enhance or allow sorbents to be more effective for mercury control. Additional testing needs to be conducted at plants whose operating temperatures are above 350ºF.

Effect of SO_3 Conditioning

Sorbent screening tests showed that SO_3 conditioning decreased the adsorption capacity of the carbon sorbents. The difference in mercury removal during the first test with and without SO_3 conditioning was 60 versus 65%, respectively. This is almost a 10% difference, which is the level of accuracy we believe is repeatable in these tests. To confirm whether SO_3 conditioning really had an impact on sorbent effectiveness, the same test conditions, 10 lbs/MMacf with and without SO_3 conditioning, were repeated with the ground FGD during the second week. The results were 60% removal with SO_3 and 63% removal without SO_3. Data from the two sets of tests indicate that there was no significant effect on mercury removal with PAC injection when SO_3 conditioning was in-service.

Parametric Test Summary

A summary of results from all the parametric tests is presented in Figure 15. This figure plots mercury removal efficiency as a function of sorbent injection concentration. The different symbols represent different test conditions. This graph shows that there was a rapid increase in mercury removal with PAC injection up to an injection concentration of about 5 lbs/MMacf. Increasing the sorbent injection rate from 5 to 10 lbs/MMacf showed an incremental 10% increase in mercury removal. No significant additional removal was observed when the rate of sorbent injection was raised above 10 lbs/MMacf.

As stated above, this apparent ceiling of 70% removal was surprising. Poor sorbent distribution in the gas stream could contribute to this problem. To prove that distribution was not a problem, several tests were conducted with the injection lances in different configurations that would alter distribution patterns. No measurable change in mercury removal was noted.

There was no significant difference in performance among the four carbons, even with the finer grain carbons. The finest carbon, Insul with a D50 of 7 microns, was difficult to feed because of bridging in the discharge legs of the silo. Design changes would have to be incorporated into this system to feed finer carbons.

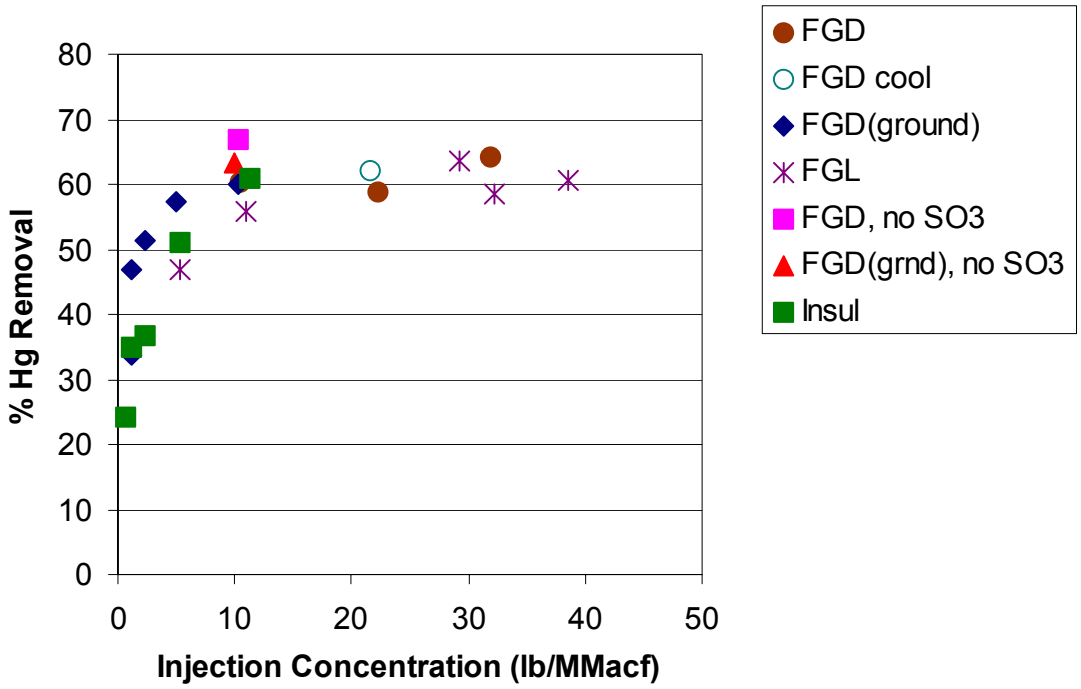

Figure 15. Mercury Removal Trends across ESP as a Function of PAC Injection Concentrations. Measurements made during Parametric Tests, September–October 2001.

One of the significant observations made during the testing was that carbon injection had no impact on the performance of the ESP. Some improvement in power levels was seen during the spray cooling tests.

Long-Term Tests

Long-term testing under optimum conditions, as determined from the parametric tests, was performed to gather data on:

- Mercury removal efficiency over time;
- The effects of sorbent injection on ESP performance and balance of plant equipment; and
- Operation of the injection equipment to determine the viability and economics of the process.

The original test plan called for injecting sorbents at one condition, 24 hours/day, for up to two weeks to obtain the highest mercury removal rates possible within equipment limitations. However, results from the parametric tests showed significant mercury removal at low injection rates. This raised interest in the long-term performance under these conditions. The long-term test was divided into three injection periods, each lasting five days, to determine:

- The ability to achieve significant mercury removal (40–50%) at a low sorbent injection concentration. The interest here was to obtain representative ash samples at this low rate to determine the impact on existing, valuable reuse of the PPPP fly ash. At 1 lb/MMacf, the estimated increase in ash LOI was 0.5%.
- Mercury removal at a high sorbent injection concentration and the impact on ESP performance. An injection concentration of 10 lbs/MMacf was chosen because no additional mercury removal was measured at higher injection rates; and
- The performance at an intermediate sorbent injection concentration of 3 lbs/MMacf.

DARCO FGD activated carbon was chosen as the sorbent for these tests. Similar to the baseline test series, mercury was measured by both the S-CEMs and the Ontario Hydro method. The Ontario Hydro measurements were performed only once during the long-term tests at the highest injection concentration, 10 lbs/MMacf. ESP performance, coal and fly ash samples, and S-CEM data were collected. Full-load boiler conditions were held between the hours of 7:00 a.m. and 8:00 p.m., with load under dispatch control at other times, except for the three days when the Ontario Hydro tests were conducted and full load was maintained 24 hours/day. Table 12 presents the schedule for the long-term tests and the goals associated with each condition.

Table 12. Long-Term Test Conditions and Goals.

Dates	Target Injection Concentration	Test Goals
10/31/01–11/04/01	1 lb/MMacf	• Minimize impact on ash • Measure mercury removal at low injection rate
11/05/01–11/09/01	3 lb/MMacf	• Measure mercury removal at logarithmic "middle" point
11/10/01–11/14/01	10 lb/MMacf	• Measure mercury removal at high injection rate • Determine impact on ESP • Conduct Ontario Hydro mercury measurements

Long-Term Test Mercury Removal Results

Figure 16 presents mercury removal with respect to PAC injection concentration for both the parametric and long-term tests. Mercury removal rates as measured with the S-CEMs for each of the three long-term test conditions can be seen as the large crosses at 1.6, 3.7, and 11.3 lbs/MMacf. These data points represent the average over the entire five-day period. The average mercury removal was 46% at 1.6, 57% at 3.7, and 66% at 11.3 lbs/MMacf. These results fall within the trends developed during the parametric tests, showing that no significant additional increase in mercury removal was achieved with longer run times.

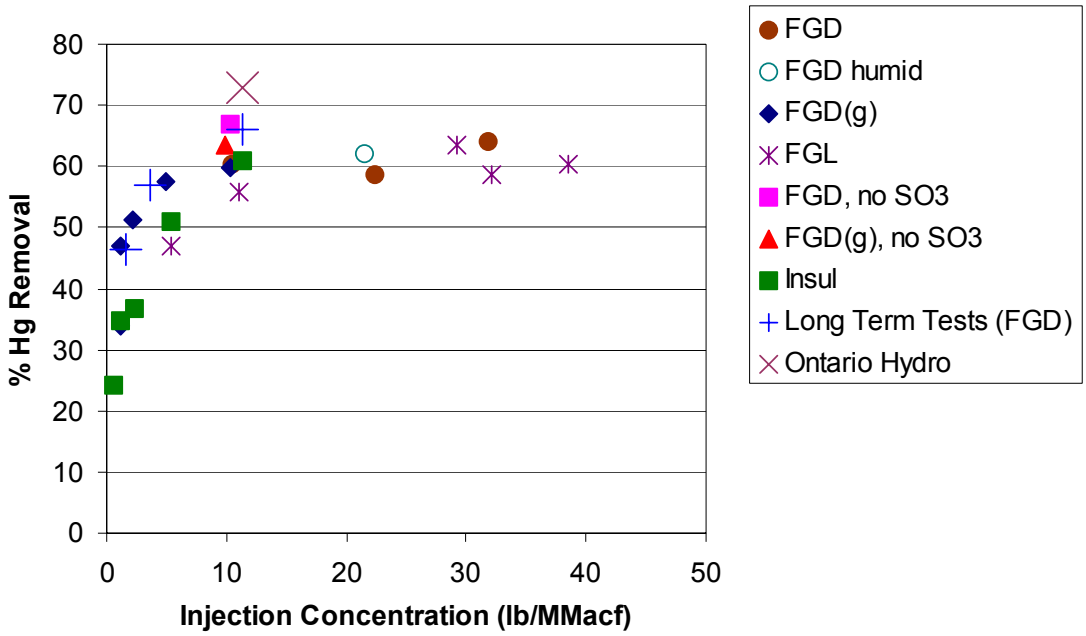

Figure 16. Mercury Removal Trends for Parametric and Long-Term Tests at PPPP.

Three sets of Ontario Hydro measurements were made at the inlet and outlet of the 2-4 ESP and the average removal efficiency is shown in Figure 16 as the large X at 11 lbs/MMacf. Results from the Ontario Hydro measurements are presented in Table 13. The average inlet mercury concentration was 17.4 µg/dncm, with over 80% being measured as elemental mercury. Coal samples taken during this period had an average mercury level of 0.133 µg/g, or an equivalent flue gas concentration of 21.7 µg/dncm. The outlet mercury concentrations show the effect of carbon injection with lower mercury emissions for all species and 70.7% and 74.5% reduction of the elemental and oxidized species respectively. The overall average reduction in total mercury was 72.9%. At the outlet the predominant species of mercury is the elemental form; however, it is still 70% less than what was present upstream of PAC injection.

Table 13. Speciated Mercury Measured by Ontario Hydro Method; Long-Term Tests at PAC Injection Concentration = 11 lbs/MMacf.

Location	Particulate (µg/dncm)[1]	Elemental (µg/dncm)[1]	Oxidized (µg/dncm)[1]	Total (µg/dncm)[1]	Total (lbs/TBtu)
ESP Inlet	1.0	14.7	1.7	17.4	12.7
ESP Outlet	0	4.3	0.4	4.7	3.4
Average RE %	**100**	**70.7**	**74.5**	**72.9**	
% of Total at Inlet	5.7	84.5	9.8		
% of Total at Outlet	0	91.5	8.5		

Note 1: Normal: T = 32 ºF, Values corrected to 3% O_2

The S-CEM and Ontario Hydro removal efficiency results show good correlation—within 10%. The was the case even though the S-CEM measures only vapor-phase mercury and the Ontario Hydro measurements showed nearly 6% particulate mercury at the inlet.

Figure 17 presents inlet and outlet mercury concentrations as measured by the S-CEMs, mercury removal across the ESP, and PAC injection concentration during the long-term test. Inlet mercury concentration varied between 10 and 17 µg/dncm. During the first two days of the long-term test at the low injection rate, outlet mercury levels slowly decreased to about 6.5 µg/dncm. Outlet mercury can be seen to follow inlet mercury levels, especially when mercury concentration increased on November 12, 2001.

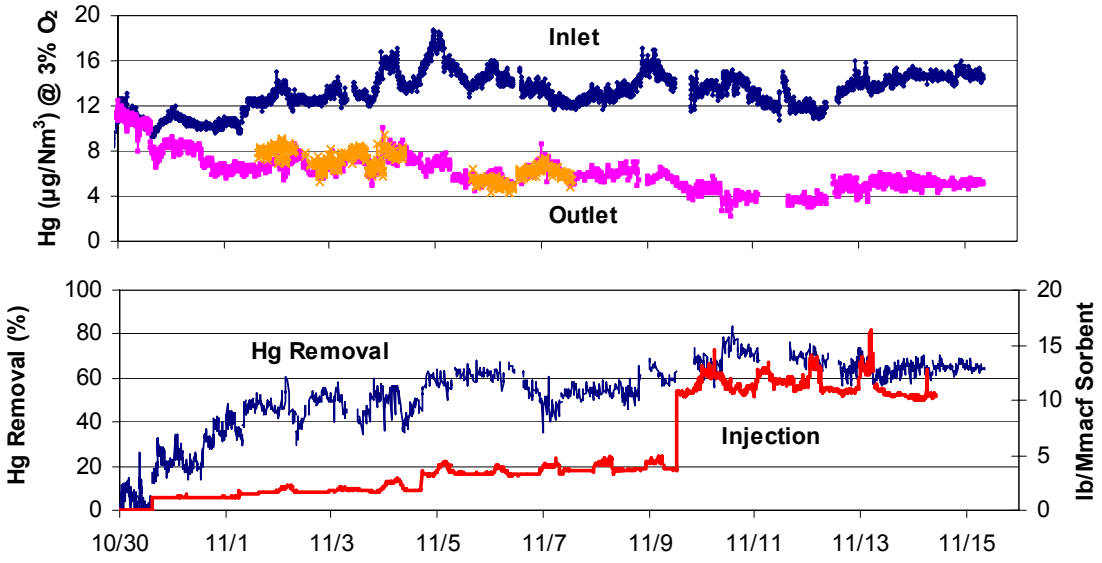

Figure 17. Inlet and Outlet Mercury Concentrations, Removal Efficiencies, and PAC Injection during Long-Term Test at PPPP; November 2001.

Conclusions

A full-scale evaluation of mercury control using activated carbon injection upstream of an ESP was conducted at Wisconsin Electric's Pleasant Prairie Power Plant Unit 2. Results and trends from these relatively short-term tests were encouraging, but identified issues with ash reuse in concrete. The overall test conclusions are:

- Mercury removal between 40–50% was obtained at a sorbent injection rate of 1 lb/MMacf.
- Mercury removal between 50–60% was obtained at a sorbent injection rate of 3 lbs/MMacf.
- Mercury removal between 60–70% was obtained at a sorbent injection rate of 10 lbs/MMacf.
- PAC injection effectively reduced both elemental and oxidized mercury concentrations.
- Fly ash could not be used for concrete with any trace of PAC present.
- No detrimental impact on ESP performance.
- On a PRB ash, if the gas temperature is below 300ºF, it appears that additional cooling does not improve mercury capture.
- Increasing sorbent injection concentration above 10 lbs/MMacf did not increase mercury removal.

BRAYTON POINT

The test objectives for Brayton Point included evaluating activated carbon injection concentrations, sorbents supplied by various manufacturers, and the effect of different injection lances designed to increase the effective spray coverage in the duct.

Site Description

PG&E National Energy Group owned and operated Brayton Point Station located in Somerset, Massachusetts, at the time of testing. There are four fossil-fuel-fired units at the facility designated as Units 1, 2, 3, and 4. In 1982, three of the four units (Units 1, 2, and 3) were converted from oil to coal. The units fire a low-sulfur, bituminous coal. Unit 1, which was the test unit, has a tangentially fired boiler rated at 245 net MW.

The primary particulate control equipment consists of two cold-side ESPs in series, with an EPRICON flue gas conditioning system that provides SO_3 for fly ash resistivity control. The EPRICON system is used on an as-needed basis. The first ESP (old ESP) in this particular configuration was designed and manufactured by Koppers. The Koppers ESP has a weighted wire design and a specific collection area (SCA) of 156 ft^2/1,000 acfm. The second ESP (new ESP) in the series configuration was designed and manufactured by Research-Cottrell. The second ESP has a rigid electrode design and an SCA of 403 ft^2/1,000 acfm. The total SCA for the unit is 559 ft^2/1,000 acfm. The precipitator inlet gas temperature is nominally about 280°F at full load.

The first precipitator consists of four parallel chambers, each with 28 gas passages 24’ long at 10” centers. Each chamber is further divided into three collecting surface fields. The first ESP has a total of 12 transformer/rectifier (T/R) sets.

The second precipitator consists of two parallel chambers. Each chamber is subdivided into 38 gas passages 54’ long at 12” centers. The chambers are then divided into six collecting surface fields. The second ESP contains a total of 24 T/R sets.

Hopper ash from both precipitators is combined in the dry ash-pull system. The ash is processed by an on-site STI carbon separation system to reduce the carbon content to approximately 2%. This processed ash is sold as base for concrete and is considered a valuable product for the Brayton Point Station. The remainder of the higher carbon ash is a disposable waste. One precipitator’s ash can be isolated from the balance of the unit, however this is a labor-intensive procedure. A summary of important descriptive parameters for Brayton Point Unit 1 is presented in Table 14.

Table 14. Site Description Summary, Brayton Point Unit 1.

Parameter Identification	Description
Process	
Boiler Manufacturer	C-E Tangential, Twin Furnace
Burner Type	C-E LNCFS III (32 burners)
Low-NO_x Burners	Yes
Steam Coils	Yes
Over Fire Air	Yes
NO_x Control (Post Combustion)	None
Temperature (APH Outlet)	280ºF
Coal	
Type	Eastern Bituminous
Heating Value (Btu/lb)	12,319
Moisture (%)	6.6
Sulfur (%)	0.72
Ash (%)	11.32
Hg (μg/g)	0.05
Cl (%)	0.08
Control Device	
Type	Cold-Side ESPs in series
ESP #1	
Manufacturer	Koppers
Design	Weighted Wire
Specific Collection Area (ft^2/1,000 afcm)	156
ESP #2	
Manufacturer	Hamon Research-Cottrell
Design	Rigid Electrode
Specific Collection Area (ft^2/1,000 afcm)	403
Flue Gas Conditioning	SO_3 Injection, EPRICON

Sorbent for mercury control was injected into the ductwork in between the two ESPs. Only one of the two inlet precipitator ducts was treated, nominally 125 MW. Figure 18 presents a diagram of the particulate control equipment at Brayton Point.

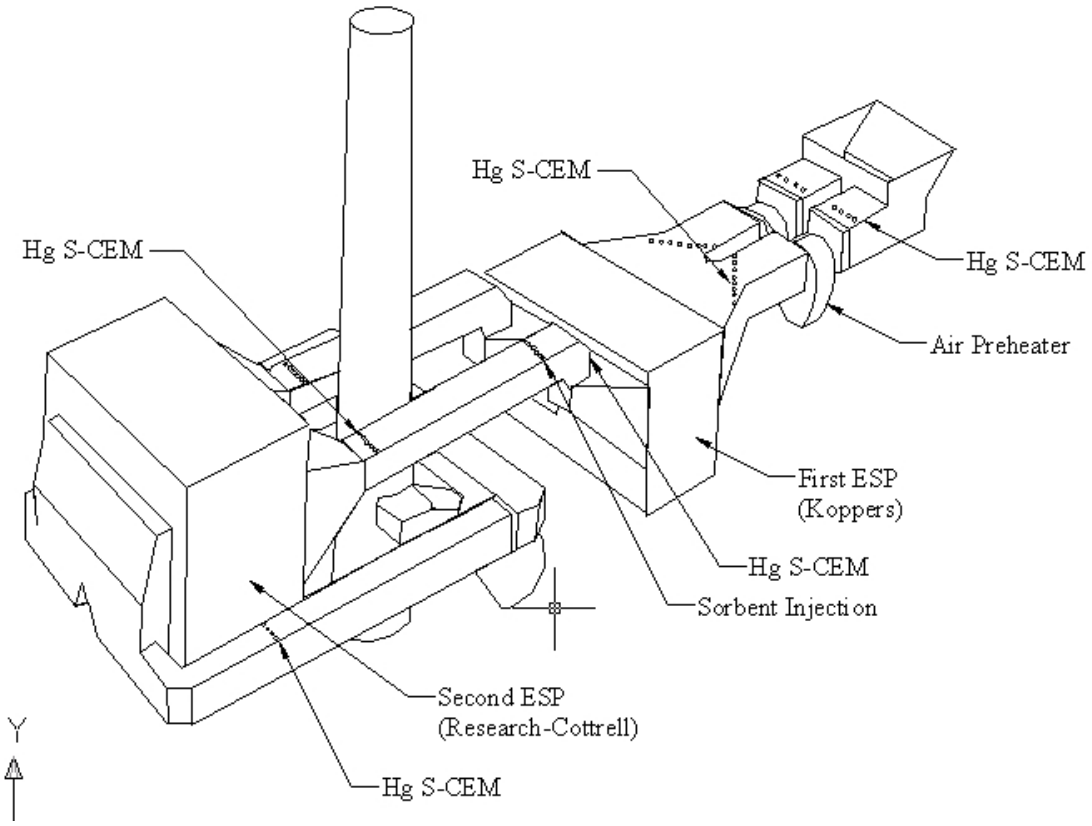

Figure 18. Isometric View of Precipitator Arrangement at Brayton Point Unit 1.

Test Results

Sorbent Screening

The first phase of field-testing was sorbent screening tests conducted by URS Corporation in February 2002. Sorbents were screened using a fixed-bed of carbon to measure the sorbents' mercury adsorption capacities. The mercury adsorption tests were carried out on a slipstream of flue gas extracted from upstream of the first precipitator, with and without SO_3 injection. Eight coal-derived sorbents, two fly-ash-based sorbents, one tire-derived sorbent, and one zeolite-based sorbent were each tested at a temperature of 275ºF. The major conclusions from the fixed-bed tests were:

- Carbons are capable of achieving high mercury capacities in Brayton Point Unit 1 flue gas;
- SO_3 appears to inhibit carbon adsorption and with certain sorbents decreased the adsorption capacity to zero. With the activated carbon products, the presence of SO_3 in the flue gas decreased the adsorption capacity in some cases by a factor of six; however, the measured adsorption capacity was still above 150 µg/g, the minimum threshold capacity established for sorbents used in an ESP configuration. Therefore performance of these sorbents should not be impacted;

- Only one of the fly-ash-based sorbents tested showed an adsorption capacity greater than 150 µg/g;
- The zeolite-based sorbent showed a low adsorption capacity in the Brayton Point flue gas; thus, this particular sorbent was not chosen for full-scale testing.

Using the results from the fixed-bed tests as one of the selection criteria, five sorbents were selected for the full-scale parametric tests. Mercury adsorption capacity measured during the screening tests are presented in Table 15.

Table 15. Results of Fixed-Bed Screening Tests by URS Corporation at Brayton Point.

Sorbent/Supplier	Base	Adsorption Capacity SO_3 Off @ 50 µg/Nm^3	Adsorption Capacity SO_3 On @ 50 µg/Nm^3
FGD/NORIT Americas	Lignite	4,314 µg/g	1,380 µg/g
HOK300/Donau Carbon	Lignite	4,786 µg/g	
CC/CARBOCHEM	Bituminous	1,948 µg/g	
SAI-B/Superior Adsorbents	Activated Carbon		1,799 µg/g
EPRI – LAC*	Activated Carbon	2,196 µg/g**	

** Data supplied by EPRI*
*** Number calculated using a different flue gas composition*

Baseline Tests

A set of baseline tests was conducted on June 6–7, 2002. During these tests, Unit 1 boiler load was held steady at "full-load" conditions during testing hours, nominally 8:00 a.m. to 6:00 p.m. Both the S-CEMs and the Ontario Hydro method were used to measure mercury across both ESPs. Previous Ontario Hydro measurements conducted at Brayton Point's Unit 1 have shown native mercury removal efficiencies ranging from 29–75%.

Results from the Ontario Hydro tests conducted during the baseline testing series showed an average native mercury removal efficiency of 90.8%. These results can be seen in Table 16. The mercury removal efficiency of 90.8% was high when compared to historical data for Brayton Point Unit 1.

Table 16. Results from Baseline Testing Series – Brayton Point Unit 1; June 2002.

Location	Particulate (μg/dncm)[1]	Elemental (μg/dncm)[1]	Oxidized (μg/dncm)[1]	Total (μg/dncm)[1]	Total (lbs/TBtu)
ESP Inlet	4.6	ND[2] <0.21	0.26	<5.1	<3.7
ESP Outlet	ND[2] <0.007	ND[2] <0.29	0.18	<0.48	<0.35
Average RE %	**>99.8%**	**N/A**	**30.8%**	**~90.6%**	

Note 1: Normal: T = 32°F, Values corrected to 3% O_2
Note 2: < values indicate measured value is below method detection limit

Parametric Testing Series

A series of parametric tests was conducted to determine the optimum operating conditions for several levels of mercury control. During this particular test series, the primary variables that were tested included injection concentration, sorbent type, and SO_3 flue gas conditioning on/off. In all, 20 different parametric conditions were tested. A summary of the parametric test conditions is presented in Table 17. For these tests, standard testing conditions are defined as Unit 1 boiler at full-load operation and the EPRICON flue gas conditioning system on. Exceptions to the standard conditions are noted in the table. Each condition was tested for a minimum of six hours.

Table 17. Summary of Parametric Testing Conditions – Brayton Point.

Test Series	Carbon Name	Target Injection Concentration (lbs/MMacf)	Testing Conditions
1–4	FGD	1, 3, 10, 20	Standard
5–6	SAI-B	3, 10	Standard
7–8	SAI-B	10, 20	Multiple Nozzle Lance
9–11	CC	3, 10, 20	Standard
12–14	HOK300	3, 10, 20	Standard
15–16	FGD	10, 20	EPRICON Off
17–18	FGD	7, 15	Standard
19–20	LAC	3, 10	EPRICON Off

A summary of results from all the parametric tests is presented in Figure 19. This figure plots mercury removal efficiency as a function of sorbent injection concentration. It is important to emphasize that this graph represents the mercury capture across the second ESP. This is incremental mercury capture that is being measured independent of the baseline mercury capture that is happening across the first ESP. The different symbols represent different test conditions including carbon type and SO_3 off (EPRICON). This graph shows that there was a direct relationship between the mercury removal efficiency and sorbent injection concentration. Mercury removal efficiencies ranged from 2–35% at the lower

sorbent injection concentration of 3 lbs/MMacf to 75–93% at the highest sorbent injection concentration of 20 lbs/MMacf.

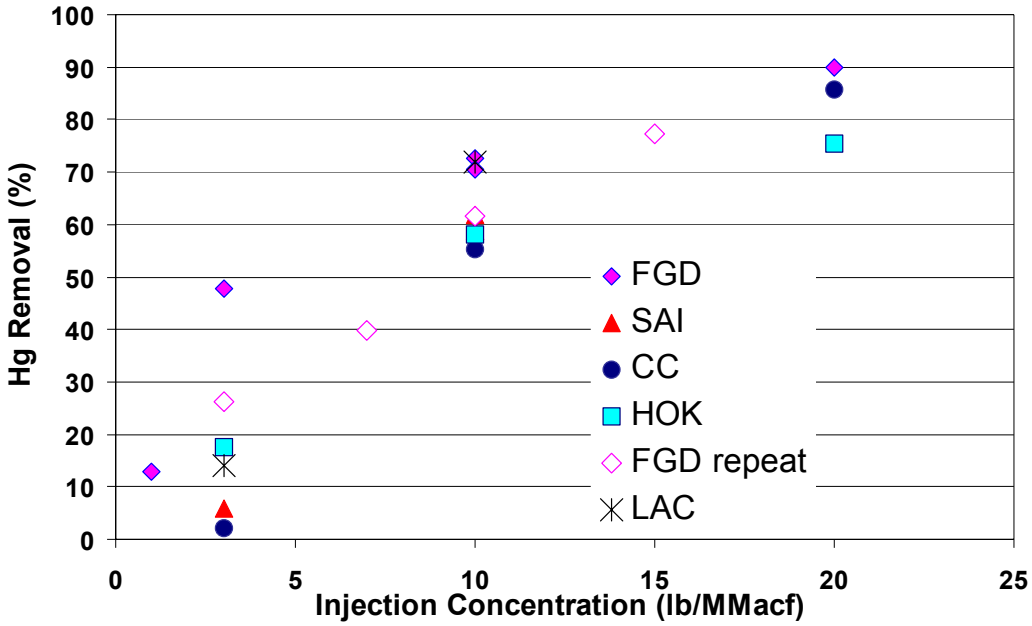

Figure 19. Mercury Removal Trends across Second ESP – Parametric Testing Summary.

One of the significant observations made during the parametric tests was that mercury removal increased above 70% with higher injection concentrations. This was in contrast with what was observed at Pleasant Prairie where increasing the sorbent injection concentration above nominally 10 lbs/MMacf resulted in almost no increase in mercury removal.

Researchers have observed that very low concentrations of HCl in the flue gas is required for standard activated carbon to effectively remove elemental mercury (Sjostrom, et al., 2002b). Activated carbon sorbent is designed to adsorb contaminants in the flue gas whether they are vapor-phase mercury, sulfur dioxides, or gaseous HCl. At Pleasant Prairie, where gaseous HCl concentrations are less than 1 ppm, once all of the HCl in the flue gas was adsorbed by the activated carbon, the effectiveness of activated carbon to capture elemental mercury was greatly reduced. This could help explain the ceiling phenomenon seen at Pleasant Prairie where the mercury removal efficiencies did not increase when sorbent injection concentrations increased above 10 lbs/MMacf.

Long-Term Testing Series

The long-term testing series was conducted over a 10-day period in which two different sorbent injection concentrations were tested. The first five days of testing called for injecting the DARCO FGD product continuously at an injection concentration of 10 lbs/MMacf. Upon completion of this test, the injection concentration was immediately increased to 20 lbs/MMacf. This test condition was maintained throughout the rest of the long-term

testing series. During both periods of testing, vapor-phase mercury was measured with the mercury S-CEMs. The average mercury removal was 91% during the 10 lbs/MMacf test and 98% during the 20 lbs/MMacf test. To verify results, mercury was also measured by the Ontario Hydro method. These results are presented in Table 18.

Table 18. Ontario Hydro Results from Long-Term Test on July 18–19, 2002, at Brayton Point; 10 lbs/MMacf and 20 lbs/MMacf ACI.

Location	Particulate (μg/dncm)[1]	Elemental (μg/dncm)[1]	Oxidized (μg/dncm)[1]	Total (μg/dncm)[1]	Total (lbs/TBtu)
Testing at 10 lbs/MMacf					
Inlet	7.9	ND[2] <0.38	0.83	<9.1	<6.6
Outlet	ND[2] <0.03	ND[2] <0.37	0.27	<0.67	<0.49
Average RE %	**>99.6%**	**N/A**	**67.5%**	**~92.6%**	
Testing at 20 lbs/MMacf					
Inlet	6.1	ND[2] <0.33	1.11	<7.6	<5.6
Outlet	ND[2] <0.05	ND[2] <0.25	0.17	<0.50	<0.37
Average RE %	**>99%**	**N/A**	**91%**	**~94.7%**	**<0.49**

Note 1: Normal: T = 32°F, Values corrected to 3% O_2
Note 2: < values indicate measured value is below method detection limit

Conclusions

Results and trends from these relatively short-term tests were encouraging. The overall test conclusions were:

- Activated carbon injection effectively reduced mercury in the flue gas.
- Mercury removal efficiencies >90% were seen during the long-term testing series with carbon injection concentrations of 10 and 20 lbs/MMacf.
- Activated carbon was shown in long-term tests to remove oxidized mercury. Elemental mercury was not detected during long-term carbon injection in any sample, so no conclusions can be drawn as to its removal.
- The presence of SO3 in the flue gas from the EPRICON flue gas conditioning system did not affect performance of the activated carbon in terms of mercury capture.
- No detrimental impact on ESP performance was observed as indicated by total power levels and stack opacity (DOE Topical Report Numbers 41005R11, 41005R12, 41005R18, 41005R21).
- The performances of different activated carbons were relatively similar at the higher injection concentrations. During the lower injection concentrations, mercury captured varied among the different sorbents. Additional testing needs to be conducted to fully document the performance variability between the alternate sorbents.

SALEM HARBOR

Test objectives for this field test program were to determine the mercury control and balance-of-plant impacts resulting from activated carbon injection into a full-scale ESP. It was also important to understand the impacts of process variables on native mercury removal (>85%). One half of the gas stream was used for these tests, or 43 MWe. Activated carbon, DARCO FGD supplied by NORIT Americas, was injected upstream of the cold side ESP, just downstream of the air preheater. Mercury capture was tested as a function of the Selective Non-Catalytic Reduction (SNCR) system, amount of unburned carbon in the fly ash, and flue gas temperature.

Site Description

PG&E National Energy Group owned and operated Salem Harbor Station located in Salem, Massachusetts, at the time of testing. There are four fossil-fuel-fired units at the facility designated as Units 1, 2, 3, and 4. Units 1–3 fire a low-sulfur, bituminous coal and use oil for startup. Unit 4 fires #6 fuel oil. Unit 1, which was the test unit, is a Babcock &Wilcox (B&W) single-wall-fired unit with twelve DB Riley CCV-90 burners. It is rated at 88 gross MW.

The particulate control equipment consists of a two-chamber, cold-side ESP (chambers designated 1-1 and 1-2), which provides two separate gas flow paths from the outlet of the tubular air heaters to the ID fan inlets. This Environmental Elements ESP has a rigid electrode design and a specific collection area (SCA) of 474 ft^2/1,000 acfm. The precipitator inlet gas temperature is nominally 295ºF at full load.

There are eight electrical fields in the direction of flow, and two across. The discharge electrodes are 44.5’ in length and are spaced 18” apart in the direction of gas flow.

There are eight precipitator ash hoppers on Unit 1, four in the direction of flow and two across. A pneumatic conveying system ties into each hopper and blows dry ash into the fly ash storage silo, where it is combined with fly ash from the ESPs, economizer hoppers, and air preheater hoppers from Units 1, 2, and 3. Both wet and dry unloading systems are available to feed the ash from the fly ash storage silo into a truck. Typical LOI/carbon content of the Unit 1 ash is about 25%. This ash is landfilled.

A summary of important descriptive parameters for Salem Harbor Unit 1 is presented in Table 19 and a schematic of the unit can be seen in Figure 20.

Table 19. Site Description Summary, Salem Harbor Unit 1.

Parameter Identification	Description
Process	
Boiler Manufacturer	B&W 85 MW Radiant Boiler
Burner Type	DB Riley CCV-90
Low-NO_x Burners	Yes
Steam Coils	Yes
Over Fire Air	No
NO_x Control (Post Combustion)	SNCR
Temperature (APH Outlet)	295
Coal	
Type	South American Bituminous
Heating Value (Btu/lb)	12,701
Moisture (%)	9.64
Sulfur (%)	0.63
Ash (%)	3.92
Hg (μg/g)	0.03
Cl (μg/g)	206
Control Device	
Type	Cold-Side ESP
ESP	
Manufacturer	Environmental Elements
Design	Cold-Side, Rigid-Electrode
Specific Collection Area (ft^2/1,000afcm)	474
Flue Gas Conditioning	None

Four test locations were used for mercury measurements on Salem Harbor Unit 1: the economizer outlet, the air preheater exit, the ESP inlet, and the ESP outlet (ID fan inlet). This allowed for mercury measurements at various locations throughout the system, including mercury removal across the ESP.

The parametric test series at Salem Harbor was unique in this program with a focus on process variables, in addition to injection of sorbent. Process variables of interest were temperature, SNCR on/off, and LOI/carbon content in the ash. These variables were successfully tested to further broaden the knowledge base for mercury control using sorbent injection and to help determine the cause for a high native mercury removal capture experienced at Salem Harbor.

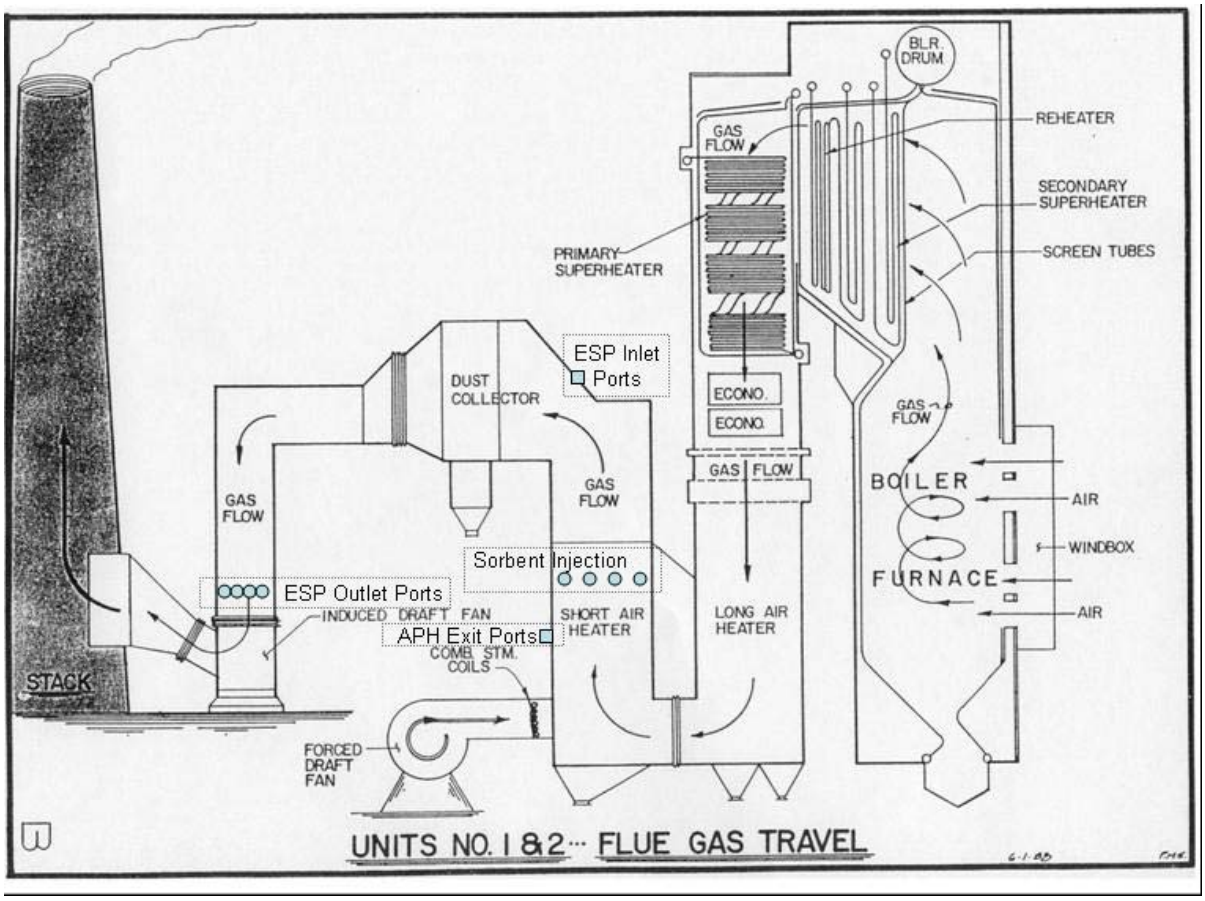

Figure 20. Flue Gas Travel and Equipment Arrangement – Salem Harbor.

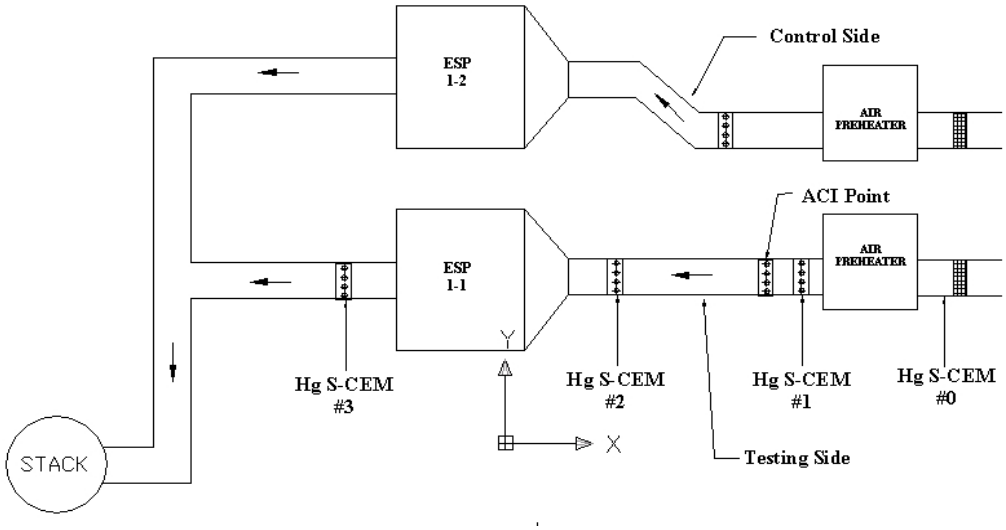

Figure 21. Plan View of Mercury Measurement Locations – Salem Harbor.

Test Results

Baseline Tests

During baseline tests, Unit 1 was held at full-load (~86 MW) under normal operating conditions. Mercury S-CEM measurements were made at locations 1, 2, and 3, which can be seen in Figure 21. In addition to the mercury S-CEM, manual measurements of mercury following the Ontario Hydro method were made. The triplicate runs of the Ontario Hydro testing method were conducted at locations 1 and 3.

Ontario Hydro results are shown in Table 20. As with prior testing, high native mercury control was seen, about 88% removal. No elemental mercury was detected in any sample. A large portion (~97%) of the total mercury is already in the ash at the inlet test location, or is adsorbed onto the ash in the sample train. This is shown in Table 20 as particulate mercury. Oxidized mercury increased across the ESP but is very low, <0.5 μg/dncm.

Figure 22 shows S-CEM measurements during the same time frame as the Ontario Hydro runs. The S-CEM measured 2–6 μg/dncm of vapor-phase mercury at the air preheater outlet (location 1 on Figure 21). ESP inlet and outlet measurements are seen to trend together across the time span. Comparing Inlets 1 and 2 on 9/23/02 shows that vapor-phase mercury is removed between the air preheater outlet (Inlet 1 total vapor-phase mercury (TVM)) and the ESP inlet (Inlet 2 TVM). However, 2–4 μg/dncm remains in the vapor phase at Location 2. This is greater than indicated by the Ontario Hydro method, which shows <0.36 μg/dncm of mercury in the vapor form at the same location (ESP inlet).

Outlet measurements made by the S-CEM confirm that some mercury is emitted from Salem Harbor Unit 1. The Ontario Hydro tests alone do not give a good metric of actual emissions since this site has emissions that are very close to the detection limit for this method. This is important for compliance demonstration at very low levels, as will be required in Massachusetts if the mercury control provisions of 310 CMR 7.29 are finalized.

Table 20. Speciated Mercury Measured by Ontario Hydro Method, Baseline Conditions. Average of Three Runs, Salem Harbor Unit 1.

Location	Particulate (μg/dncm)[1]	Elemental (μg/dncm)[1]	Oxidized (μg/dncm)[1]	Total (μg/dncm)[1]	Total (lbs/TBtu)
ESP Inlet	10.15	ND<0.27	0.09	<10.5*	<7.7*
ESP Outlet	ND<0.34	ND<0.50	0.41	<1.2	0.87
Average RE %	>97%	--	**Increase**	**~88%**	
% of Total at Inlet	97%	2.6%	0.9%	--	
% of Total at Outlet	**27%**	**40%**	**33%**	--	

Note 1: Normal: T = 32°F, Values corrected to 3% O_2
** Individual test runs were 7 to 14 μg/dncm*

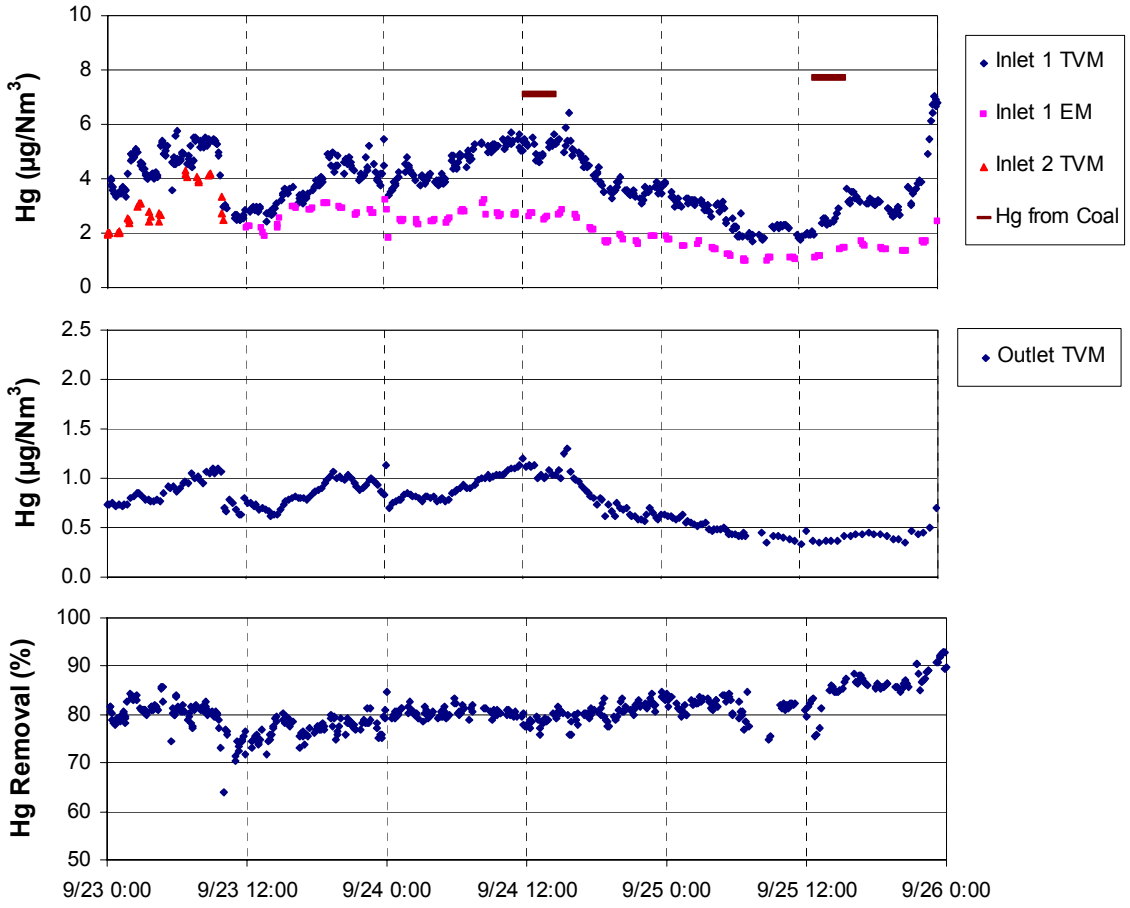

Figure 22. Baseline S-CEM Data from Salem Harbor, September 2002. All Measurements, Including Removal Percentages, are Vapor-Phase Mercury Only.

Three coal samples collected on 9/23, 9/24, and 9/25/02 during the baseline tests were analyzed for mercury and showed concentrations of 0.07–0.08 µg/g. At Salem Harbor, this coal mercury level is equivalent to a mercury concentration of about 7–8 µg/dncm @ 3% O_2 in the flue gas.

Parametric Tests

The two primary objectives of the parametric testing series were 1) to evaluate certain process variables and determine their roles for mercury capture and 2) to evaluate the effect of activated carbon injection on mercury removal. The equipment configuration at Salem Harbor Unit 1 allowed the evaluation of the following variables:

- SNCR
- Unburned carbon in the fly ash (LOI)
- Flue Gas Temperature
- Activated Carbon Injection (ACI)

Parametric Tests – No Sorbent Injection

Parametric testing without sorbent injection evaluated mercury removal as a function of SNCR on and off, flue gas temperature and fly ash LOI.

Selective Non-Catalytic Reduction (SNCR)

Salem Harbor's Unit 1 utilizes a urea-based SNCR system to help reduce NO_x emissions. Minimal data are available to assess the affect of SNCR on mercury capture, and there is some debate in the industry as to its potential effectiveness. With permission from the Massachusetts Department of Environmental Protection (MADEP), along with plant personnel, Salem Harbor's Unit 1 operated at full load (~ 86 MW) without the SNCR system upon start-up from a week-long outage. This ensured the system was free of any residual ammonia and helped quantify the impacts of SNCR on mercury capture.

During the period in which Unit 1 operated without the SNCR system, vapor-phase mercury measurements were made throughout the system with the S-CEM. With the SNCR system out of service, vapor-phase mercury removal efficiencies ranged from 80–95%, which can be seen in Figure 23.

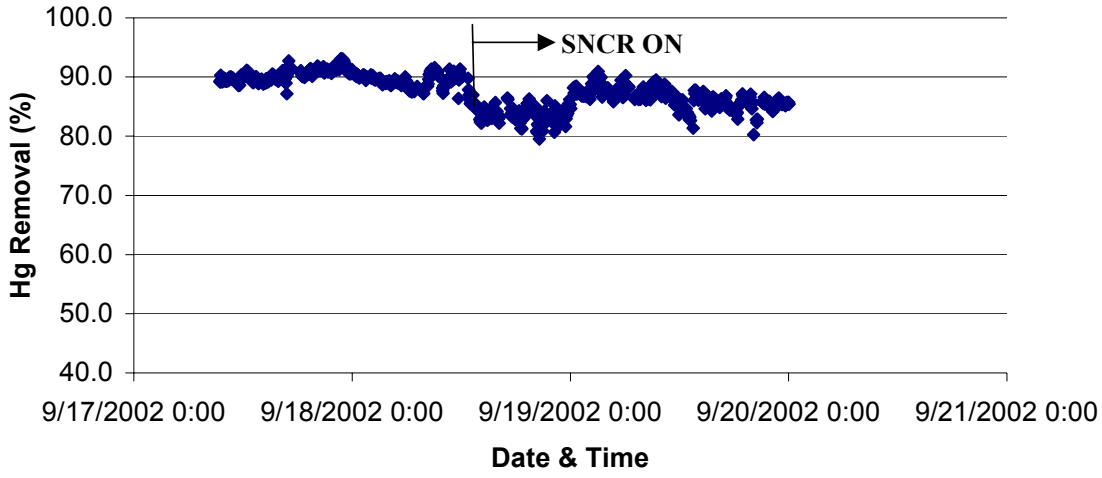

Figure 23. Vapor-Phase Mercury Concentrations during SNCR Testing.

When the SNCR was turned on, there was no increase in mercury removal. If anything, the data show slightly lower and more variable mercury removal with SNCR on; however, mercury levels were changing during this period and the variation in mercury removal seen in Figure 23 should be considered insignificant because of the variation in the coal mercury content.

LOI

The next series of tests without sorbent injection evaluated the impact of reducing load, and consequently LOI, on the native mercury removal. Late on September 25, 2002, boiler load was reduced to 65 MW, with a drop in LOI from about 35% to about 20%. No significant change was seen in mercury removal. Although there was a brief uptick in mercury at the inlet and outlet of the ESP when this change was made, once things stabilized the outlet mercury levels recovered to about 0.5 μg/dncm (Figure 24). It is possible that within the range of operational flexibility, taking LOI from 35% to 20%, was not sufficient to produce a reduction in mercury removal efficiency due to reduced LOI because the quantity of LOI/carbon in the flue gas was still high. Reducing LOI below 10%, although not feasible during this test series, may show a reduced mercury control impact.

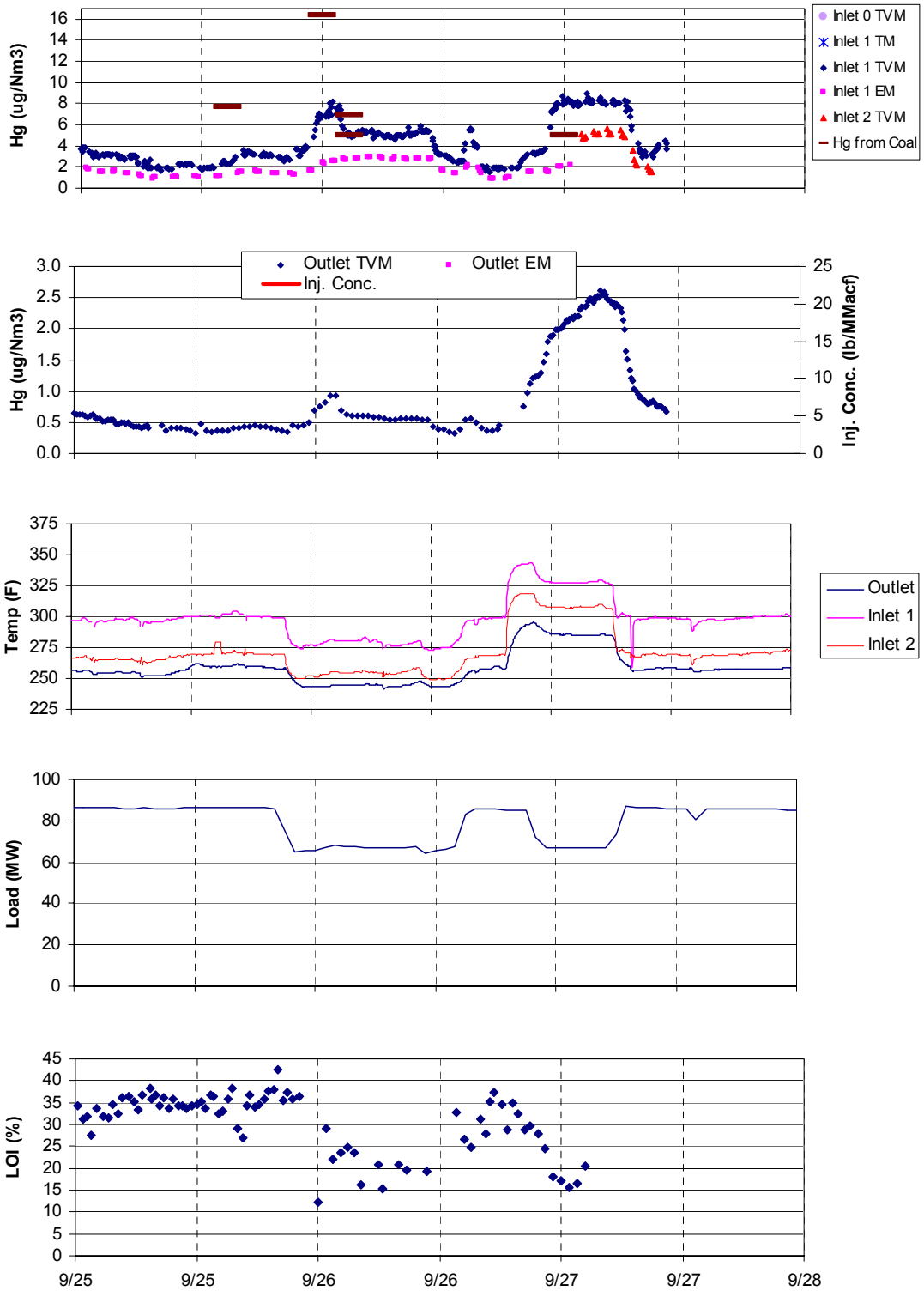

Figure 24. S-CEM Mercury Levels and Process Conditions during Parametric Tests with No Sorbent Injection. Salem Harbor Unit 1; September 25–27, 2002.

Temperature

The final parameter evaluated before sorbent injection was the role of flue gas temperature on mercury capture. Salem Harbor Unit 1 had the ability to increase ESP inlet flue gas temperatures 50ºF by placing the steam coils in service. These steam coils were located just downstream of the exhaust side of the forced draft (FD) fan and upstream of the air preheater. Under normal operating conditions, ESP inlet temperatures averaged approximately 300ºF. Placing the steam coils in service, the average ESP inlet temperature increased to 350ºF.

During the parametric series, the steam coils were placed into service while Unit 1 was held steady at full load (~ 86MW). ESP inlet temperatures were increased from 300ºF to 350ºF. Increasing the flue gas temperature decreased the overall removal efficiency for the vapor-phase mercury from ~90% to the 10–20% range. This can be seen in Figure 25 below. Figure 25 also identifies different LOI levels present in the flue gas. As the flue gas temperature increased, the mercury removal efficiency decreased independent of the LOI levels present in the flue gas.

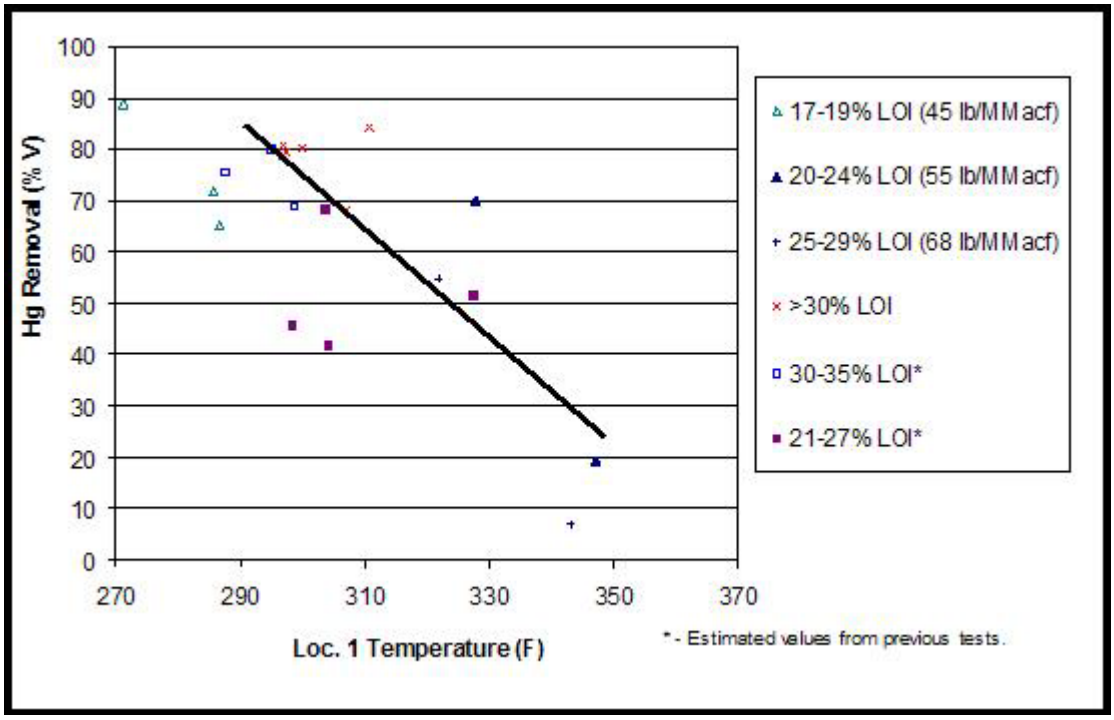

Figure 25. Mercury Removal Efficiency vs. Temperature (No Sorbent Injection).

Parametric Tests – Sorbent Injection

Sorbent injection was tested to determine whether further removal beyond the 90% removal measured in baseline conditions was possible. At Salem Harbor just one sorbent was tested, the benchmark activated carbon sorbent, NORIT America's DARCO FGD.

A challenge with these parametric tests was the low mercury concentrations at the outlet and the difficulty of accurately measuring at these levels. Mercury concentration at the outlet prior to sorbent injection generally was less than 0.5 µg/dncm and as low as 0.1 µg/dncm. Measuring at these concentrations is difficult and accurately measuring a reduction from this level posed an additional challenge.

During the parametric testing series, it should be noted that a different coal was being fired. This test coal was a low-sulfur bituminous coal and generally showed a lower baseline mercury capture as compared to the standard coal fired during the baseline series.

Figure 26 presents mercury removal efficiencies at various sorbent injection concentrations and different flue gas temperature ranges during the parametric tests. The results show that there were inconclusive trends when activated carbon was added at standard operating temperatures, 280–290ºF. This is likely due to the relatively high LOI carbon concentrations at temperatures where the LOI was effectively removing mercury. At the mid-temperature range of 322–327°F, the LOI lost some of its ability to capture vapor-phase mercury; however, activated carbon performed relatively well. The addition of activated carbon did increase mercury removal and the trend showed the expected correlation between injection concentration and mercury removal. At the hotter temperature range of 343–347°F, ACI performance was severely impacted and maximum removal efficiency was nominally 45%.

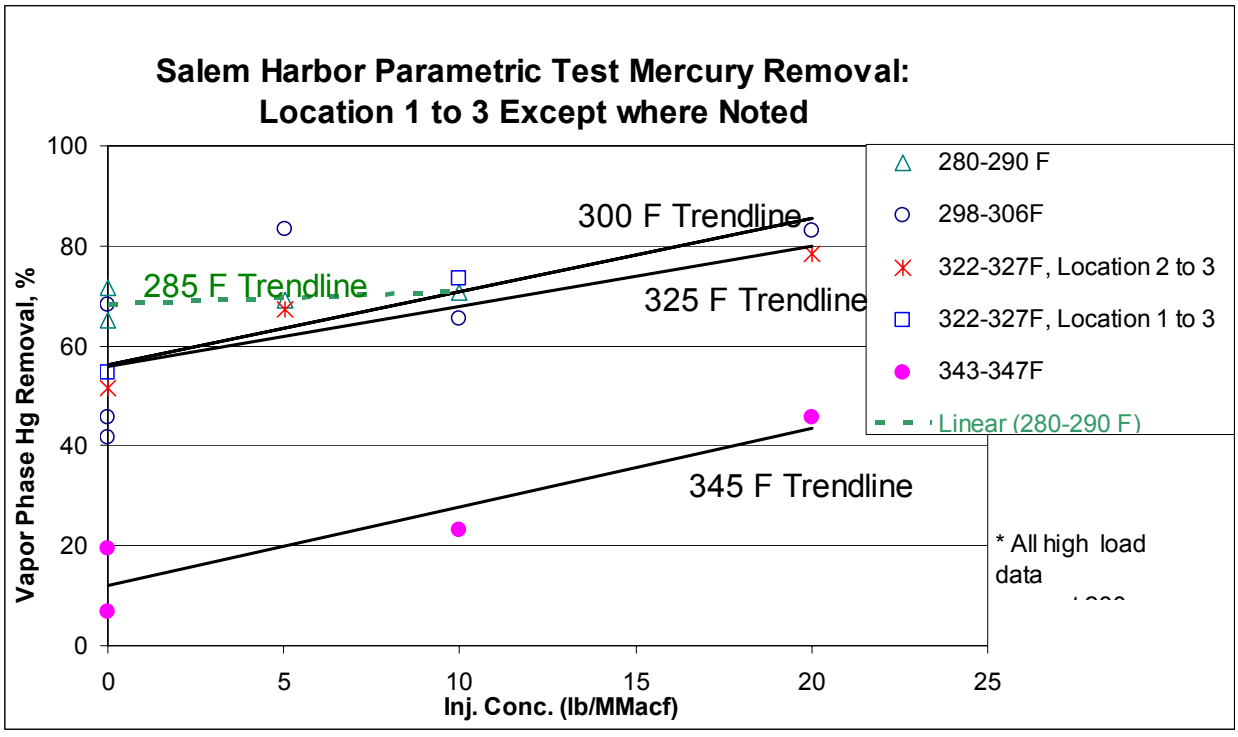

Figure 26. Vapor-Phase Mercury Removal at Salem Harbor Unit 1 as a Function of Sorbent Injection Rate and Flue Gas Temperature.

Long-Term Tests

Activated carbon was injected continuously November 19–22, 2002, at an injection concentration of 10 lbs/MMacf. Measurements were conducted periodically at four locations and are shown on Figure 27. The vapor-phase mercury during these tests was very low, in the range of 1.5–4 µg/dncm upstream of the air preheater, dropping across the air preheater to 0.3–1.3 µg/dncm. Because of the low concentrations at most of the measurement locations, long sampling times were required by the S-CEMs (longer sample times provide lower detection limits for mercury), limiting the number of samples that could be taken for elemental vs. total mercury.

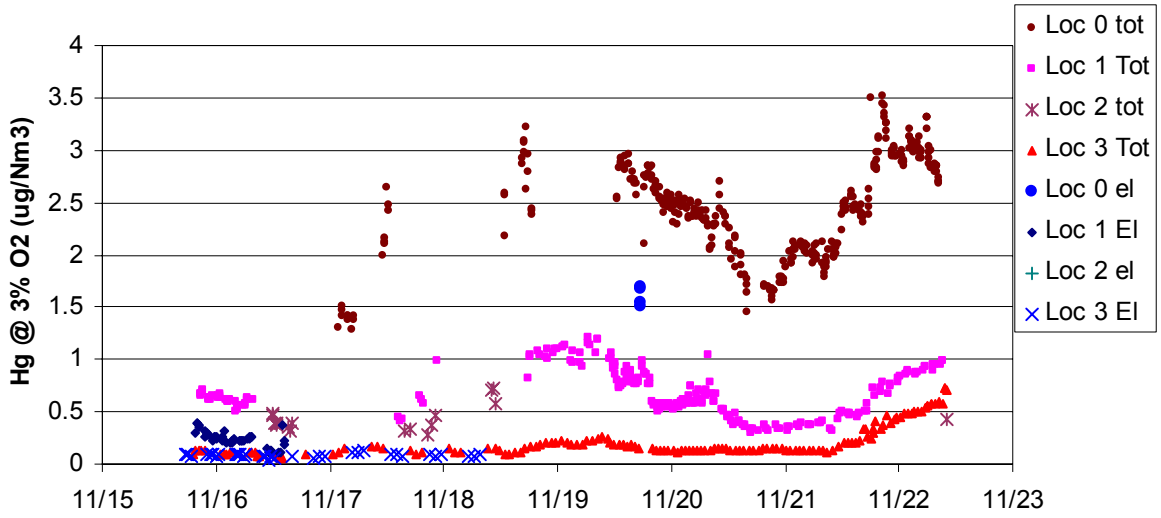

Figure 27. Vapor-Phase Mercury Trends as Measured by the S-CEMs during Long-Term Test Series, Salem Harbor Unit 1.

Triplicate Ontario Hydro measurements were made on November 21, 2002. As shown in Table 21, the vapor-phase mercury levels are very low, with elemental mercury less than the method detection limit at both the inlet and outlet locations. Coal mercury analyses obtained during the long-term tests showed an equivalent flue gas mercury concentration range of 5–8 µg/dncm. The major differences between this result with PAC injection and the baseline tests (Table 20) without PAC are:

- The total mercury (upstream of the ESP) during long-term tests was about half that present during the baseline series (5.24 vs. 10.5 µg/dncm);
- Oxidized mercury increased across the ESP during baseline tests, while it was removed by the ACI during long-term tests;
- The residual mercury indicated for both baseline and long-term tests is predominantly based on method detection limits and not on actual readings. Oxidized mercury has a

lower detection limit than particulate or elemental. The oxidized mercury that is emitted drops from 0.41 to 0.02 µg/dncm with the addition of the PAC.

- S-CEM measurements during baseline testing confirm that some mercury is emitted, in the range of ~0.3–1.3 µg/dncm. This corresponds to about 0.0033–0.0145 lbs/GW-hr. In comparison, testing during the long-term ACI injection series showed emissions generally in the range of 0.15 to 0.25 µg/dncm (although emissions did increase towards the end of this run to over 0.5 µg/dncm). This corresponds to about 0.0016–0.0027 lb/GW-hr.

Table 21. Ontario Hydro Results from Long-Term Test on November 21, 2002, at Salem Harbor Unit 1; 10 lbs/MMacf ACI.

Location	Particulate (µg/dncm)[1]	Elemental (µg/dncm)[1]	Oxidized (µg/dncm)[1]	Total (µg/dncm)[1]	Total (lbs/TBtu)
ESP Inlet	4.9	ND<0.27	0.07	<5.2	<3.8
ESP Outlet	ND<0.09	ND<0.51	0.02	<0.6	<0.44
Average RE %	**>98%**	**--**	**70%**	**~88%**	
% of Total at Inlet	94%	2.6%	0.9%	--	
% of Total at Outlet	15%	82%	3%	--	

Note 1: Normal: T = 32 ºF, Values corrected to 3% O_2

Conclusions

A full-scale evaluation of mercury control using activated carbon injection upstream of a cold-side ESP on a low-sulfur bituminous coal was conducted at PG&E NEG's Salem Harbor Unit 1. This comprehensive test program answered many questions about the potential for mercury control via activated carbon injection at Salem Harbor, increased the understanding of the effect of process variables and also pointed to several areas in which more information is needed. Results and trends from these relatively short-term tests were encouraging, reinforcing ACI as a solution for mercury control if process conditions change such that baseline removal is impaired.

- The native removal of mercury under normal operating conditions ranged from 80–95%. Coal mercury produces flue gas with mercury content typically in the range of 5–8 µg/dncm, but occasionally spikes to twice this level.
- Baseline mercury emissions at Salem Harbor ranged from ~0.3 to 1.3 µg/dncm. This corresponds to about 0.0033–0.0145 lbs/GW-hr. In a one-week test, ACI resulted in emissions of 0.0026–0.0036 lb/GW-hr via Ontario Hydro, which is at the Ontario Hydro detection limit for both particulate and elemental mercury.

- The native removal of mercury drops as temperature is increased, with removal starting to fall off above 320ºF and dropping dramatically at temperatures greater than 340ºF.
- LOI reduction in the range tested did not affect mercury removal. LOI was reduced from about 35% to about 17% with no effect on mercury removal.
- The urea-based SNCR system was tested (on/off) for any impact on mercury removal; none was observed.
- Under normal operating conditions, activated carbon had a small affect on overall mercury capture, which was already very high.
- Activated carbon injection successfully removed vapor-phase mercury at temperatures under 330ºF. When flue gas temperature is increased above 340ºF, the effectiveness of PAC was significantly reduced.
- At about 10 lbs/MMacf, or 210 lbs/hr sorbent injection, incremental removal of about 35 to 60% could be obtained over the native removal. This resulted in continuous overall mercury capture of 85–95% as demonstrated by S-CEM measurements in a four-day test at flue gas temperature of about 325ºF.

MERCURY CAPTURE TRENDS FOR COLD-SIDE ESPS

This section of the report provides a concise summary of the data trends obtained from the cold-side ESP plants tested in the program.

IMPACT OF COAL TYPE ON MERCURY REMOVAL

Figure 28 presents full-scale data from Brayton Point, burning a low-sulfur bituminous coal, and Pleasant Prairie, burning a Powder River Basin (PRB) coal. In both cases, mercury removal increases with increased rates of carbon injection. For the PRB coal, mercury removal was limited to 70% across the ESP. A similar limited removal trend was observed during EPRI slipstream tests on sites burning PRB coals (Sjostrom, et al., 2002b). This behavior is likely a function of the coal and resulting mercury speciation and flue gas constituents.

Very low concentrations of HCl in the flue gas are required for standard activated carbon to effectively remove elemental mercury (Sjostrom, et al., 2002b). Activated carbon sorbent is designed to adsorb contaminants in the flue gas whether they are vapor-phase mercury, sulfur dioxides, or gaseous HCl. At Pleasant Prairie, where gaseous HCl concentrations are less than 1 ppm, once all of the HCl in the flue gas was adsorbed by the activated carbon, the effectiveness of activated carbon to capture elemental mercury was greatly reduced. This helps explain the apparent ceiling phenomenon observed at Pleasant Prairie where the mercury removal efficiencies did not increase when sorbent injection concentrations increased above 10 lbs/MMacf.

In contrast to the Pleasant Prairie results, at Brayton Point, burning a low-sulfur bituminous coal, mercury removal exceeded 90% at the highest carbon injection rate. This coal has a high chloride level that results in high concentrations of HCl. Theory suggests that oxidized mercury adsorption is not as sensitive to the presence of HCl in the flue gas. At Brayton Point, the predominant species of mercury is the oxidized form and there is approximately 150 ppm of HCl present in the flue gas. These two factors create an environment in the flue gas for activated carbon to capture both forms of mercury—oxidized and elemental—at all injection concentrations. Thus, as can be seen in Figure 28, increasing activated carbon injection for bituminous coal results in continuing increases in the amount of mercury capture.

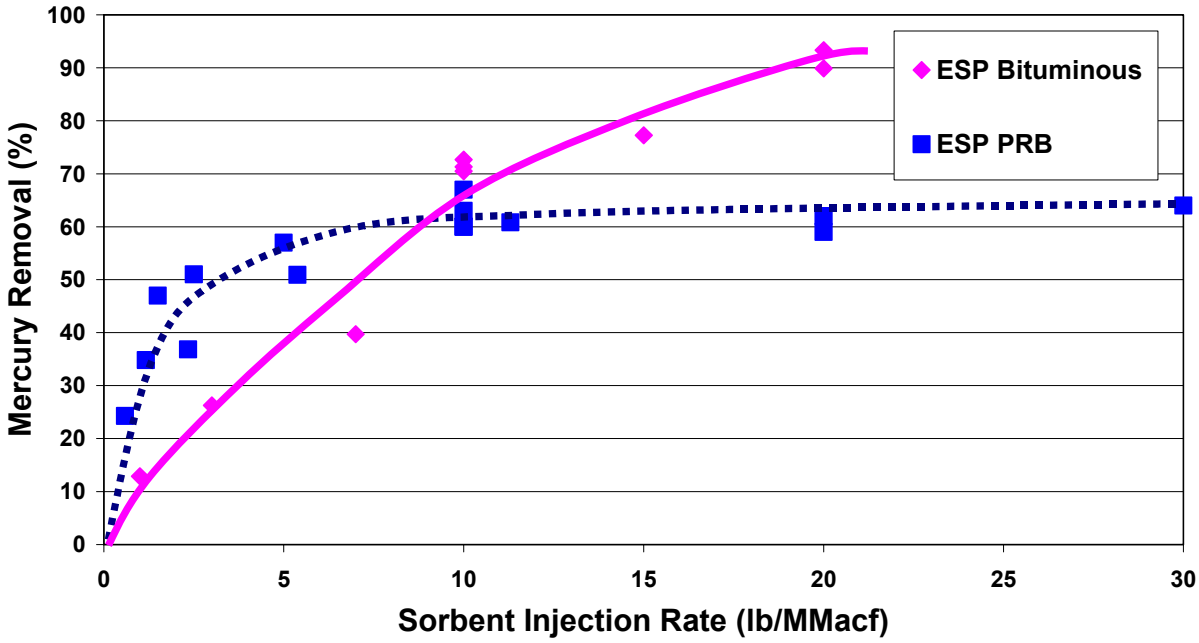

Figure 28. Comparison of Mercury Removal Performance with PAC at PPPP (PRB Coal) and Brayton Point (Low-Sulfur Bituminous Coal).

IMPACT OF GAS TEMPERATURE ON MERCURY REMOVAL

Analysis of ICR data show that mercury capture across ESPs and fabric filters was strongly dependent upon flue gas temperature and unburned carbon levels. It is believed that this phenomenon is due to the fact that while unburned carbon has very low capacity to hold on to mercury, this capacity significantly increases at lower temperatures. For example, decreasing the temperature from 300ºF to 250ºF could result in a factor of ten increase in capacity. For this reason, plants with high carbon levels and low temperatures showed the highest mercury capture.

The importance of temperature was expected to diminish somewhat when activated carbon was injected to capture mercury. As shown in Figure 29, activated carbon has a very high capacity to hold on to the captured mercury, in excess of a thousand micrograms of mercury per gram of carbon at temperatures below 300ºF. This represents excess capacity as the carbon is only exposed to the flue gas long enough to capture about one hundred micrograms of mercury per gram of carbon.

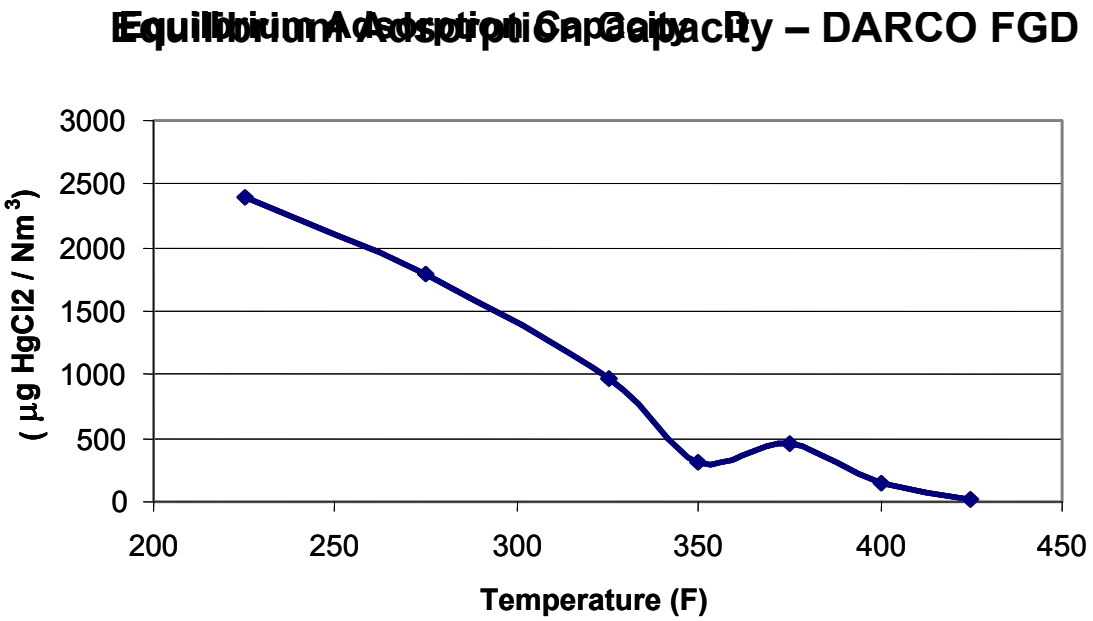

Figure 29. Sorbent Adsorption Capacity vs. Temperature – Graph Developed by URS Corporation.

The full-scale field tests described in this report provided the means to evaluate the role of temperature in mercury removal. A spray cooling system was installed and operated during the Pleasant Prairie tests. The equipment was installed upstream of carbon injection and provided the capabilities of cooling the gas by up to 50ºF. Mercury measurements were made while injecting activated carbon at the normal operating temperature of 300ºF and with the spray cooling system operating to cool the gas to 250ºF. There was no impact on mercury removal with activated carbon from spray cooling. As expected, since the sorbents had a significant amount of excess capacity, increases in capacity at the lower temperature did not result in a change in overall mercury removal.

There was also interest in evaluating the impact of higher operating temperatures on both native mercury removal and the performance of activated carbon. At the Salem Harbor Station, placing the steam coils in service could increase temperature by up to 50ºF. Under normal operating conditions, ESP inlet temperatures averaged approximately 300ºF.

During the parametric test series, the steam coils were placed into service while Unit 1 was held steady at full load (~86 MW). ESP inlet temperatures were increased from 300ºF to 350ºF. The data plotted in Figure 30 show that without injecting activated carbon, the mercury removal by the unburned carbon was extremely sensitive to the gas temperature. For all operating conditions, increasing the flue gas temperature decreased the overall removal efficiency for the vapor-phase mercury from ~90% to the 10–20% range.

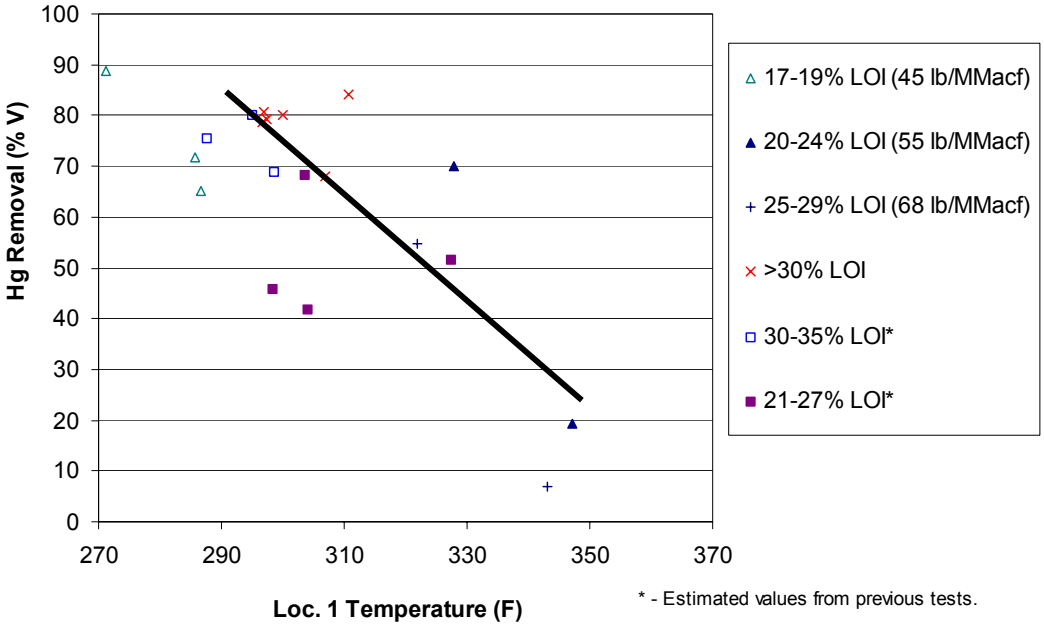

Figure 30. Mercury Removal Efficiency vs. Temperature (No Sorbent Injection).

Temperature can also be important relative to activated carbon performance at very high temperatures. Figure 31 shows a comparison of performance with activated carbon injection at Brayton Point and Salem Harbor. At Brayton Point, removal levels exceeding 90% were achieved with activated carbon at average temperatures of 300ºF. However, at Salem Harbor, at the hotter temperature range of 343–350ºF, activated carbon performance was severely impacted and maximum mercury removal efficiency was nominally only 45%. Therefore, some form of cooling may be required for applications where the flue gas temperature exceeds 340ºF. Since both of these test sites had predominantly oxidized mercury in the flue gas, it is not known whether the performance of activated carbon on gas streams with predominantly elemental mercury will be as sensitive to temperature. Additional testing on a site burning a western coal will be required to determine the maximum temperature for effective mercury capture.

RESIDENCE TIME REQUIRED FOR MERCURY REMOVAL

One key issue to be considered in the retrofit application of activated carbon injection to a large number of plants is whether there will be sufficient residence time available upstream of the ESP for the sorbent to react with the mercury.

Residence time is the total amount of time available for carbon and mercury interaction in the system. In-duct residence time represents the smallest of the three components of residence time available for a reaction between an injected sorbent and mercury in the flue gas. In addition to the ducting upstream of the ESP, additional residence time is available in the ESP inlet cone and the ESP chamber.

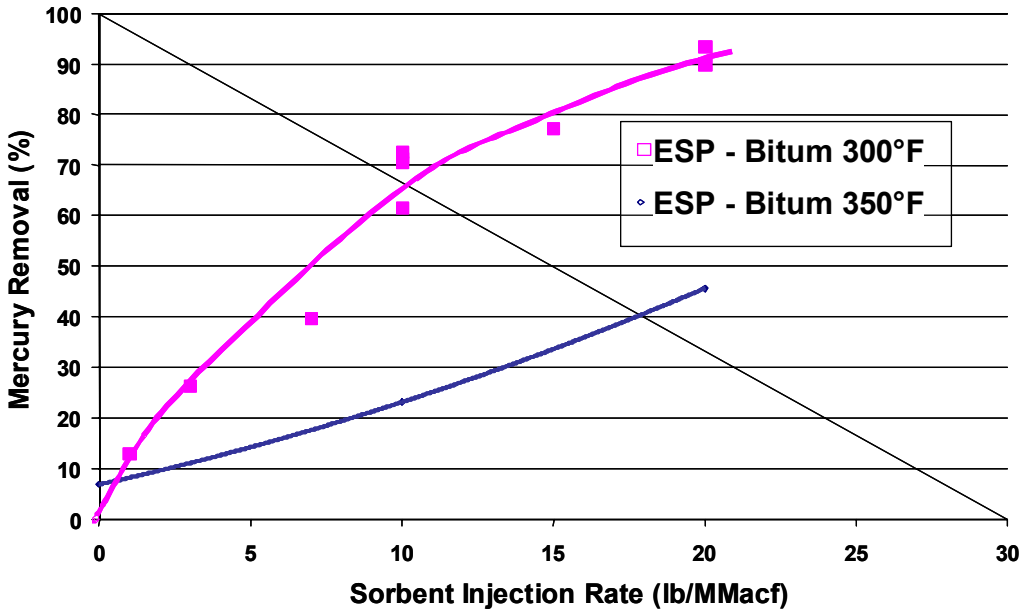

Figure 31. Temperature Impacts on the Performance of Activated Carbon on Gas Streams Containing Predominantly Oxidized Mercury.

Table 22 shows a comparison of the residence time available in these three areas for the three ESP test sites in this program. As can be seen, the ESP cone provides time for reaction that is two to three times as long as that available in the ducting. Greater time is available in the ESP, but much of this cannot be considered to play a role because a significant amount of carbon is removed in the front fields of the ESP. However, because of the apparent fast reaction between the mercury and the activated carbon, and the time available in the ducting and the ESP cone, there should be sufficient time for the process to perform in a large number of plants.

Table 22. Total Residence Time for Interaction between Activated Carbon and Mercury.

Plant	In-Duct (Seconds)	ESP Cone (Seconds)	ESP Box (Seconds)
Brayton Point	0.54	1.5	12
Salem Harbor	0.9	1.6	18
Pleasant Prairie	0.75	3.1	14.7

COAL AND ASH ANALYSIS

Since the purpose of controlling emissions from coal-fired boilers is to reduce potential buildup of mercury compounds in lakes and streams, the stability of the captured mercury in the ash and other coal combustion byproducts (CCBs) is a critical component of the overall control scheme. The ICR program showed that currently approximately 30 tons per year of mercury is contained in CCBs. Mercury control regulations could result in an additional 20 to 40 tons per year of mercury in CCBs. Also, there is a concern over the impact of powdered activated carbon in ash being sold for use in concrete.

In the U.S., approximately 67% of all fly ash produced from utility coal combustion is disposed of in landfills or surface impoundments. The remaining 33% is used for a variety of commercial applications. There are approximately 600 waste disposal sites for CCBs in the U.S., half are landfills and half are surface impoundments. Note that here CCBs include other streams such as bottom ash and scrubber sludge. A 1999 EPA study estimated that about half of the CCB landfills and a little less than a third of the surface impoundments have some type of liner, the most common type being compacted clay (Senior, et al., 2002).

Volatilization of mercury from landfills was estimated by EPA to be small. To date, there has been no evidence based on laboratory leaching studies for leaching of large amounts of mercury from fly ash under landfill conditions. Leaching appears to be the most likely pathway for liberation of mercury from fly ash. Volatilization may be important for certain applications of fly ash as filler in concrete applications. Volatilization is, of course, the primary pathway for mercury if fly ash is used as a raw material in cement kilns. However, volatilization will be complete in this case.

PAC injection applied to coal-fired boilers will result in the fly ash being mixed with a certain amount of mercury-containing sorbent. This material will be sent to land disposal or used in specific applications (assuming that the presence of the sorbent is compatible with the application). Ash samples with PAC were evaluated in the four demonstration programs.

The Gaston sample (the product of a bituminous coal) collected from the baghouse downstream of the ESP had a high LOI and mercury content, in spite of the low sorbent injection rate, because most of the ash was removed upstream of the COHPAC® baghouse by a hot-side ESP. Thus, the sample had a relatively high proportion of sorbent. The Pleasant Prairie sample (the product of a subbituminous coal) had a low LOI and mercury content. Sorbent was injected upstream of an ESP and was combined with the full ash stream. The LOI and mercury content were much lower than the Gaston sample. There was little or no detectable mercury leached by ASTM water leach methods (TCLP and SGLP - including 30- and 60-day leaching), or sulfuric acid leach (bituminous ash). Samples were also analyzed by CONSOL as part of another DOE program. They also found no leaching of mercury from PAC (Withum, et al., 2002).

Although the ash with PAC appears to be highly stable, initial testing of the PRB ash from Pleasant Prairie determined that the presence of even trace amounts of activated carbon in the

ash rendered the material unacceptable for use in concrete. Even though the (PRB) ash conformed to the ASTM C-618 standard for Class C fly ash, it did not pass the Foam Index test that is also required for sale of this ash for use in concrete formulation. The foam index test is used to determine the amount of Air Entrainment Additives needed to meet freeze-thaw requirements. This means that with PAC injection, the plant would not only lose revenues from ash sales, it would incur additional expenses to landfill the material.

At Brayton Point the amount of LOI in the ash appeared to correlate with the mercury or chlorine contents in the ash collected in the second (new) ESP. This correlation did not appear to be as strong in the first (old) ESP; however, it is difficult to draw conclusions from so few samples. During the baseline testing series, the unburned carbon (LOI) in the ash may have adsorbed both mercury and chlorine. With the chlorine content in the flue gas at elevated levels, this may have contributed to the elevated mercury capture experienced during the baseline testing series.

In the Brayton Point samples, the amount of mercury leached during the TCLP and SGLP leaching protocols was about 100 times lower than the primary drinking water standard. There was no clear difference between the first ESP and second ESP in terms of mercury leached from the samples.

During the long-term tests at Salem Harbor, mercury in the fly ash increased from control side levels of ~0.12 µg/g up to as high as ~0.38 µg/g with 10 lbs/MMacf ACI. Based on coal analyses, if all the mercury was in the ash, the ash would contain an average of about 1 µg/g mercury. All samples that were leach-tested showed very low levels of mercury leaching. Leaching tests with ACI resulted in the same or less mercury leaching than baseline or control side tests. Comparing the measured values of <0.01 to 0.034 mg/L with the standard of 0.2 mg/L, it is clear that this ash would be acceptable for landfill disposal.

In summary, the analyses indicate:

- The amount of LOI in the ash appears to correlate with the mercury or chlorine contents of the ash.
- Results from both the leaching protocols (TCLP and SGLP) indicate the amount of mercury leached from the samples was about 100 times lower than the primary drinking water standard.
- As expected, the mercury content in the ash appears to increase with increased activated carbon injection.

COSTS

The costs of process equipment and annual sorbent usage have been estimated for each site. Size and design were established based on the long-term test results for approximately 90% mercury control. These estimates, using 2005 pricing, are summarized in this section. Topical reports specific to each site provide installation estimates and other site-specific O&M costs (DOE Topical Report Numbers 41005R11, 41005R12, 41005R18, 41005R21).

GASTON

The estimated uninstalled cost for a sorbent injection system and storage silo for the 270-MW Unit 3 is about $640,000 ± 30% ($2.37/kw). Sorbent costs were estimated for nominally 80% mercury control based on the long-term PAC injection concentration of 1.5 lbs/MMacf. For Gaston Unit 3, this would require an injection rate of nominally 80 lbs/hr. Assuming a unit capacity factor of 80% and a delivered cost of $0.50/lb for PAC, the annual sorbent cost for injecting PAC into the existing COHPAC® baghouse would be about $300,000 ($0.16/MWh).

PLEASANT PRAIRIE

The estimated uninstalled cost for a sorbent injection system and storage silo for the 612-MW Unit 2 is $1,300,000 ± 30% ($2.12/kw). Sorbent costs were estimated based on a long-term PAC injection concentration of 10 lbs/MMacf. For PPPP Unit 2, this would require an injection rate of nominally 1,400 lbs/hr. Assuming a unit capacity factor of 80% and a delivered cost for PAC of $0.50/lb, the annual sorbent cost for injecting PAC into the existing ESP would be about $5,000,000. PAC costs for 50% control at an injection concentration of 1 lb/MMacf would be about $600,000 annually ($0.14/MWh).

BRAYTON POINT

The estimated uninstalled cost for a sorbent injection system and storage silo for the 250-MW Unit 1 is $680,000 ± 10% ($2.72/kw). Costs were estimated based on a long-term activated carbon injection concentration of 10 lbs/MMacf. For Brayton Point Unit 1, this would require an injection rate of nominally 600 lbs/hr. Assuming a unit capacity factor of 80% and a delivered cost for PAC of $0.50/lb, the annual sorbent cost for injecting PAC into the existing ESP would be about $2,100,000 ($1.20/MWh).

SALEM HARBOR

The estimated uninstalled cost for a sorbent injection system and storage silo for 80–90% mercury control on the 86-MW Unit 1 is $620,000 ± 10% ($7.21/kw). Costs were estimated based on a long-term PAC injection concentration of 10 lbs/MMacf. For Salem Harbor Unit 1, this would require an injection rate of nominally 210 lbs/hr. Assuming a unit capacity factor of 65% and a delivered cost for PAC of $0.50/lb, the annual sorbent cost for injecting PAC into the existing ESP would be about $570,000 ($1.16/MWh).

COST ESTIMATE SUMMARY

Results from the field tests conducted to date indicate different levels of mercury removal can be achieved depending on the particulate control device and flue gas conditions. Data collected from the field tests at Gaston and Brayton Point showed mercury removal levels of up to 90% with COHPAC® and an ESP. At Pleasant Prairie, 50–70% control was the maximum achievable mercury control, with the configuration of an ESP collecting PRB ash. Figure 32 presents a summary of the mercury removal trends developed in this program and the projected annual sorbent costs of PAC in mills/kWh ($/MWh).

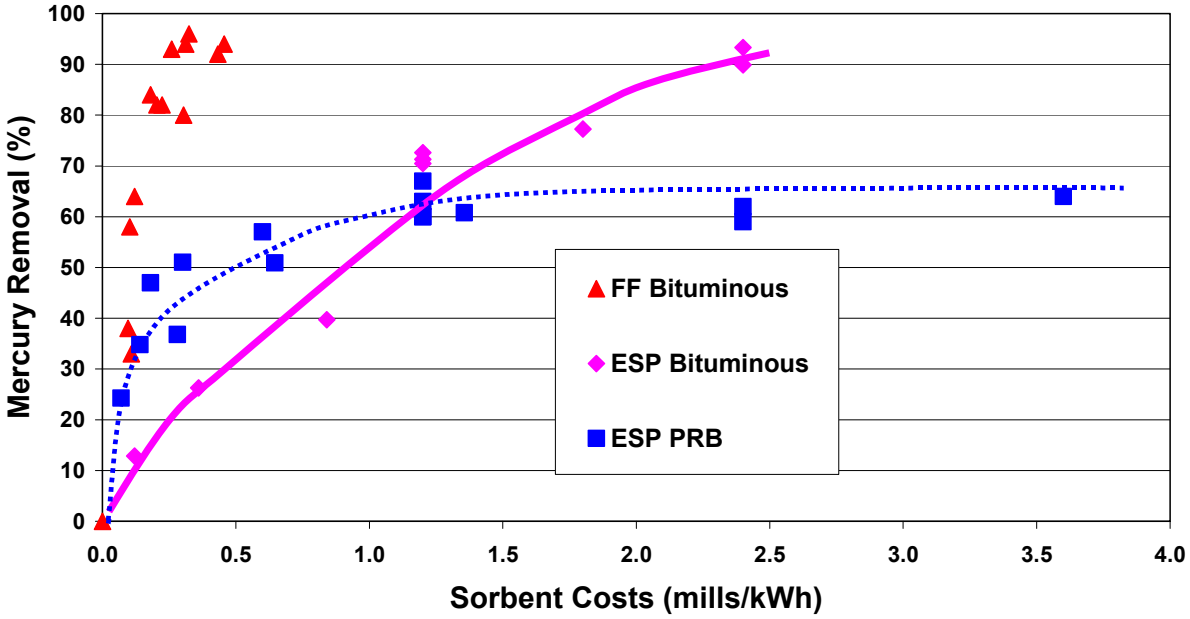

Figure 32. Comparison of Projected, Annual Sorbent Costs for ESPs on PRB and Bituminous Coals, and for a COHPAC® Fabric Filter.

CONCLUSIONS

The power industry in the U.S. is faced with meeting new regulations to reduce the emissions of mercury compounds for coal-fired plants. These regulations are directed at the existing fleet of nearly 1,100 boilers and new coal-fired boilers. A reliable retrofit technology is needed for these plants that minimizes the amount of new capital equipment while providing continued flexibility in fuel selection.

ADA-ES evaluated activated carbon injection for mercury control at four different power plants in 2001 and 2002. These tests were conducted on a portion of the gas stream at each site, with flows ranging from 260,000 to 600,000 acfm, or the equivalent of 44 MWs to 150 MWs. Three sites had cold-side ESPs as the primary particulate control device and one site had a hot-side ESP followed by a COHPAC fabric filter. Activated carbon was injected upstream of the cold-side ESPs and the COHPAC fabric filter. Parameters that were tested included:

- Electrostatic precipitator configuration;
- Fabric filter, in the COHPAC configuration;
- Eastern low-sulfur bituminous coals;
- PRB coal;
- Activated carbon injection concentrations, from 1 to 30 lbs/MMacf;
- Activated carbons and ash-based sorbents from different suppliers;
- Flue gas temperatures, (lowered temperature by spray cooling and increased temperature by the use of steam coils);
- Selective non-catalytic reduction (SNCR) for NO_X control on and off;
- SO_3 conditioning on and off; and
- LOI carbon percentage.

Test results showed that fabric filters and ESPs have distinctly different mercury removal characteristics. This was expected because the dust cake on a fabric filter bag provides a better mechanism for contact between vapor-phase mercury in the flue gas and the activated carbon particles than what occurs in an ESP. Testing also showed that with an ESP, activated carbon performance is different when low-sulfur bituminous coals are fired versus PRB coals. These performance trends are summarized in Figure 33.

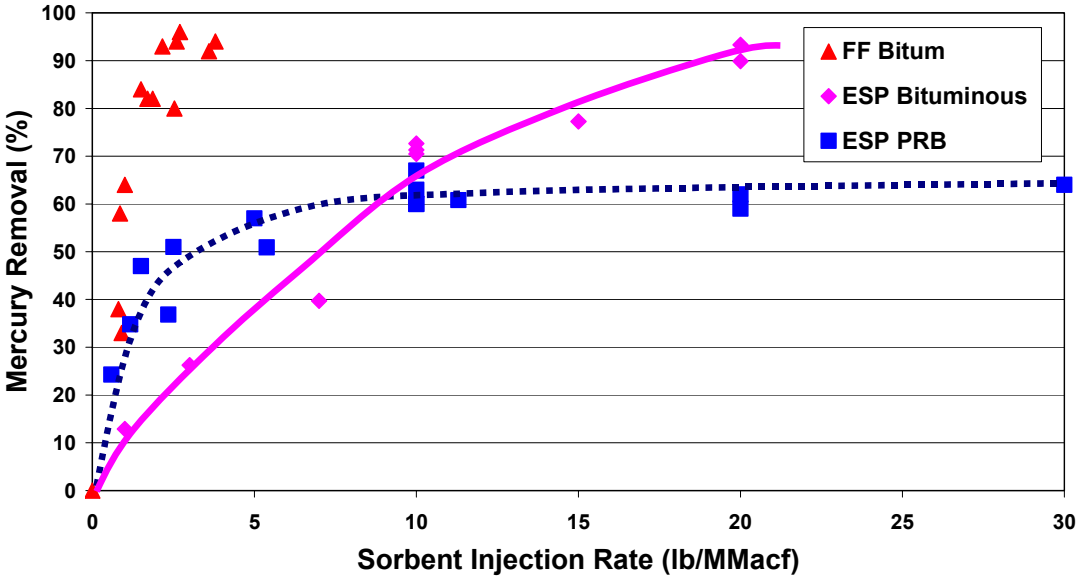

Figure 33. Comparison of Mercury Removal with Activated Carbon on a COHPAC® Fabric Filter and ESPs with both Bituminous and PRB Coals. Data Collected on Testing Conducted under DOE Cooperative Agreement DE-FC26-00NT41055 in 2001 and 2002.

This set of curves became the point of reference for a number of groups debating mercury control regulations, including DOE, EPA, utility MACT working group, state regulators, national policy developers, and other researchers. Data from this program provided a basis for more meaningful discussions regarding activated carbon injection technology, its capabilities, cost, and information gaps relative to a utility mercury regulation. More than eighty publications and presentations were made over a four-year period on the results from this program. A list of these publications can be found in the attached Appendix.

The overall conclusions from this program are:

- Activated carbon injection achieved up to 90% mercury removal for short operating periods on a COHPAC fabric filter.
- An average of 78% removal was achieved over a ten-day period at a lower than optimum injection rate on a COHPAC fabric filter.
- For new COHPAC or TOXECON fabric filters contemplated for mercury control, the design must take into consideration the additional particulate loading produced from activated carbon or other sorbents.
- Using standard non-treated activated carbons, 70% mercury removal was achieved on an ESP with PRB coal.
- Using non-treated activated carbons, 90% mercury removal was achieved on an ESP with low sulfur bituminous coal.

- Activated carbon effectively removed both elemental and oxidized forms of mercury on both bituminous and PRB coals.
- Typical capital costs for activated carbon systems were estimated to be <$3/kW.
- Annual sorbent costs were estimated to be between $0.2 to $1.5/MWh, depending on the particulate control device.
- On a PRB coal, reducing flue gas temperature below 300ºF did not improve mercury capture.
- On a bituminous coal, higher flue gas temperatures reduced native mercury removal, with a dramatic reduction above 340ºF.
- On a bituminous coal, effective mercury reduction was achieved with activated carbon injected at temperatures below 330ºF.
- Reducing the concentration of unburned carbon in the ash from 35% to 17% did not affect native mercury removal on an ESP with bituminous coal.
- A urea-based SNCR system had no impact on native mercury removal.
- SO_3 flue gas conditioning had no impact on mercury removal with activated carbon on an ESP with either bituminous or PRB coals.
- The performance of different activated carbons was relatively similar at injection concentrations above 5 lbs/MMacf.
- No detrimental impact on ESP performance was observed (ESPs in this program had SCAs >300 ft^2/1,000 acfm, which is considered relatively large).
- On a COHPAC fabric filter, injecting activated carbon increased cleaning frequency.
- Even trace amounts of activated carbon rendered PRB ash unacceptable for use in concrete.
- Little or no detectable Hg was leached by the TCLP or SGLP procedures for any of the ash samples.

REFERENCES

1. Durham, M., J. Bustard, T. Starns, C. Martin, R. Schlager, C. Lindsey, K. Baldrey, and R. Afonso (2002). "Full-Scale Evaluations of Sorbent Injection for Mercury Control on Power Plants Burning Bituminous and Subbituminous Coals," Power-Gen 2002, Orlando, FL, December 10–12.

2. Kilgroe, J.D. and R.K Srivastava (2001). "EPA Studies on the Control of Toxic Air Pollution Emissions from Electric Utility Boilers," *Air & Waste Management Association's Magazine for Environmental Managers*, pp 30-36, January.

3. Miller, R., W. Harrison, B. Corina, K. Cushing and R. Chang (1999). "COHPAC (Compact Hybrid Particulate Collector) The Next Generation in Particulate Control Technology Alabama Power Company's E. C. Gaston Units #2 and #3 "A Success Story". Presented at the EPRI-DOE-EPA Combined Utility Air Pollution Control Symposium: The MEGA Symposium, Atlanta Georgia, August 16 – 20, 1999.

4. Senior, C., J. Bustard, K. Baldrey, T. Starns and M. Durham (2003). "Leaching Studies of Fly Ash from Full-Scale Demonstration of Sorbent Injection for Mercury Control on Coal-Fired Power Plants," The Mega Meeting: Power Plant Air Pollution Control Symposium, Washington D.C., May 19–22.

5. Sjostrom, S., J. Bustard, M. Durham and R. Chang (2002a). "Mercury Removal Trends and Options for Coal-Fired Power Plants with Full-Scale ESPs and Fabric Filters," Nineteenth Annual International Pittsburgh Coal Conference, Pittsburgh, PA, September 23–27.

6. Sjostrom, S., T. Ebner, R. Slye, R. Chang, M. Strohfus, J. Pelerine and S. Smokey (2002b). "Full-Scale Evaluation of Mercury Control at Great River Energy's Stanton Generating Station using Injected Sorbents and a Spray Dryer/Baghouse," Air Quality III Conference, Arlington, VA, September 9–12.

7. Withum, J.A., A.M. Schwalb and R.M. Statnick (2002). "Characterization of Coal Combustion By-Products for the Re-Evolution of Mercury into Ecosystems," Air Quality III Conference, Arlington, VA, September 9–12.

APPENDIX

Durham, M.D. (2004). "Advances in Mercury Control Technology to Meet Future Needs," presented at PowerGen, Orlando, FL, November 30–December 2.

Bustard, C.J. (2004). "Full-Scale Evaluation of Mercury Control by Injecting Activated Carbon Upstream of ESPs and Fabric Filters," presented at the Air & Waste Management Association Rocky Mountain States Section 2004 Technical Fall Conference, Denver, Colorado, September 30.

Durham, M.D. (2004). "Impact of Pending Mercury Regulations on Coal Purchasing and Transportation," Presented at the National Coal Transportation Association Fall Meeting, Denver, CO, September 20–22.

Durham, M.D. (2004). "Performance and Costs of Mercury Control Technology for Coal Fired Boilers," presented at the MARAMA Mercury Workshop, Cherry Hill, NJ, September 13–14.

Bustard, J. (2004). "Regulation and Control of Mercury from Western Coals," presented at Utah Mining Association's 89th Annual Convention, Park City, UT, August 26.

Bustard, J. (2004). "Integrating Fabric Filters with New Multi-Pollutant Controls", presented at APC Round Table and Expo, Snowbird, UT, August 9.

Schlager, R (2004). "Mercury and Coal-Fired Power Plants – Where Are We?" presented at Southwest Chemistry Workshop, Colorado Springs, CO, July 28.

Bustard, J. and M. Durham (2004). "Air Pollution Control Equipment New Technology Acceptance Process," presented at AWMA 97th Annual Conference & Exhibition, Indianapolis, IN, June 22–25.

Durham, M. (2004). "Status and Capabilities of Mercury Control Technologies," presented at Institute of Clear Air Companies, Washington, DC, June 9–11.

Durham, M. (2004). "Performance and Costs of Mercury Control Technology for Bituminous Coals," presented at NC DAQ Mercury and C02 Workshop, Raleigh, NC, April 19–21.

Glesmann, S., J. Bustard, T. Starns, S. Sjostrom, C. Martin, R. Schlager, M. Durham, R. Chang, S. Renninger (2004). "Full-Scale Results of Mercury Control by Injecting Activated Carbon Upstream of ESPs and Fabric Filters," presented at Electric Power 2004, Baltimore, MD, March 30–31.

Durham, M. (2004). "Multi-Emissions Controls: Impacts on Fuel Choice," presented at ACC's 2004 Mercury & Multi-Emissions Seminar, Irving, TX, March 24–25.

Durham, M., J. Bustard, T. Starns, S. Sjostrom, C. Lindsey, C. Martin, R. Schlager, R. Chang, S. Renninger, L. Monroe and D. Johnson (2004). "Full-Scale Results of Mercury Control by Injecting Activated Carbon Upstream of ESPs and Fabric Filters," presented at EUEC 2004, Tucson, AZ, January 20–21.

Durham, M., J. Bustard, T. Starns, S. Sjostrom, C. Lindsey, C. Martin, R. Schlager, R. Chang, S. Renninger, L. Monroe and D. Johnson (2003). "Full-Scale Results of Mercury Control by Injecting Activated Carbon Upstream of ESPs and Fabric Filters," presented at PowerGen 2003, Las Vegas, NV, December 10.

Durham, M., J. Bustard, T. Starns, S. Sjostrom, C. Lindsey, C. Martin, R. Schlager, R. Chang, S. Renninger, L. Monroe and D. Johnson (2003). "Full-Scale Results of Mercury Control by Injecting Activated Carbon Upstream of ESPs and Fabric Filters," presented at ICAC Forum '03, Nashville, TN, October 15.

Martin, C., S. Renninger, R. Chang, L. Monroe, D. Johnson, B. Wright and M. Kane (2003). "Full-Scale Evaluation of Mercury Control by Injecting Carbon Upstream of ESPs," Air Quality IV, Arlington, VA, September 24.

Sjostrom, S., J. Bustard, M. Durham and R. Chang (2003). "Key Parameters Impacting Mercury Control for Coal-Fired Power Plants," Air Quality IV, Arlington, VA, September 24.

Durham, M. (2003). "Status and Capabilities of Mercury Control Technology: Policy Implications," Air Quality IV, Arlington, VA, September 22.

Durham, M.D. (2003). "Field Test Program to Develop Comprehensive Design, Operating and Cost Data for Mercury Control," presented at the DOE/NETL Mercury Control Technology R&D Program Review Meeting, Pittsburgh, PA, August 12.

Martin, C. (2003). "Mercury Workshop," Reinhold ESP/Fabric Filter Environmental Conference, Panama City, FL, August 11.

Durham, M., J. Bustard, T. Starns and R. Afonso (2003). "Full-Scale Evaluation of Sorbent Injection for Mercury Controls on Power Plants Burning Bituminous and Subbituminous Coals," Clean Air 2003, 7th International Conference on Energy for a Clean Environment, Lisbon, Portugal July 7–10

Durham, M.D. (2003). "Control of Mercury Emissions from Power Plants Burning Western Coals," Rocky Mountain Electrical League, June 27.

Schlager, R., S. Sjostrom, J. Bustard, M. Durham, R. Chang and S. Glesmann (2003). "Mercury Removal Trends and Options for Coal-Fired Power Plants Burning Low-Rank Fuels," Low-Rank Fuels Symposium, Billings, MT, June 25.

Durham, M. (2003). "Control of Mercury Emissions from Power Plants Burning Western Coals," Colorado Air Quality Commission, Denver, CO, June 19.

Senior, C.; J. Bustard, K. Baldrey, T. Starns, and M. Durham (2003). "Leaching Studies of Fly Ash from Full-Scale Demonstration of Sorbent Injection for Mercury Control on Coal-Fired Power Plants," The Mega Meeting: Power Plant Air Pollution Control Symposium, Washington, DC, May 19–22.

Starns, T., J. Bustard, M. Durham, C. Martin, R. Schlager, S. Sjostrom, C. Lindsey, B. Donnelly**,** R. Afonso; R. Chang and S. Renninger (2003). "Results of Activated Carbon Injection Upstream of Electrostatic Precipitators for Mercury Control," The Mega Meeting: Power Plant Air Pollution Control Symposium, Washington, DC, May 19–22.

Durham, M.D. (2003). "Mercury Emissions Trading: Technical Issues," presented at Emissions Marketing Association, Phoenix, AZ, May 5.

Durham, M. (2003). "Tools for Planning & Implementing Mercury Control Technology," *American Coal Council*, Volume 1, May.

Durham, M.D. (2003). "Tools for Planning & Implementing Mercury Control Technology. American Coal, pp. 43-46, April.

Durham, M.D. (2003). "Potential Impacts of Mercury Control Regulations on Coal Purchasing," presented at National Coal Transportation Association, Napa, CA, April 22.

Durham, M.D. (2003). "Mercury & Multi-Emissions Control Technologies: Sorbent Injection," presented at the Mercury & Multi-Emissions Compliance: Strategies and Tactics meeting, American Coal Council, Charlotte, NC, March 26.

Senior, C., C.J. Bustard, K. Baldrey, T. Starns and M. Durham (2003). "Characterization of Fly Ash from Full-Scale Demonstration of Sorbent Injection for Mercury Control on Coal-Fired Power Plants," presented at the 28th International Technical Conference on Coal Utilization & Fuel Systems, Clearwater, FL, March 10–13.

Durham, M.D. (2003). "Results from Four Full-Scale Field Tests of ACI for Control of Mercury Emissions," presented at the Utility MACT Working Group meeting, Washington, DC, March 4.

Durham, M.D. (2003). "Western Coal Characteristics/Mercury Removal Technologies," Subbituminous Energy Coalition, Mercury Information Exchange Forum, Cheyenne, WY, February 13.

Durham, M.D., C.J. Bustard and C.E. Martin (2003). "ADA-ES/DOE Mercury Control Program," presentation to EUEC Conference, Phoenix, AZ, January 28.

Bustard, C.J. and C.E. Martin (2003). "Background on Control of Mercury Emissions," presentation to Harris Group, Denver, CO, January 15.

Durham, M.D., (2003). "Review of Mercury Control Options for Western Power Plants Burning Bituminous and Subbituminous Coals",presentation to Western Associates, Denver, CO, January 8.

Durham, M.D. and C.J. Bustard (2002). Program Status Report, U.S. Department of Energy, Pittsburgh, PA, December 19.

Durham, M.D., C.J. Bustard, T. Starns, C. Martin, R. Schlager, C. Lindsey, K. Baldrey, R. Afonso (2002). "Full-Scale Evaluations of Sorbent Injection for Mercury Control on Power Plants Burning Bituminous and Subbituminous Coals," presented at Power-Gen 2002, Orlando, FL, December 10–12.

Durham, M.D. (2002). "ADA-ES/DOE Mercury Control Program," presentation to Burns & McDonnell, Kansas City, MO, December 2.

Bustard, C.J., M. Durham, C. Lindsey, T. Starns, K. Baldrey, C. Martin, R. Schlager, S. Sjostrom, R. Slye, S. Renninger, L. Monroe, R. Miller and R. Chang (2002). "Gaston Demonstrates Substantial Mercury Removal with Sorbent Injection," *Power Engineering*, pp. 93–100, November.

Durham, M.D. (2002). "Mercury Control Program," presentation to Shaw, Stone and Webster, Denver, CO, November 4.

Durham, M.D. (2002). "Impacts of Coal Characteristics on Mercury Control Strategies," presentation to 20th Annual Coal Marketing Strategies Conference, American Coal Council, Tucson, AZ, October 16.

Schlager, R., J. Bustard, M. Durham, C. Lindsey, T. Starns, K. Baldrey, C. Martin, S. Sjostrom, S. Renninger and R. Chang (2002). "Field Evaluations of Sorbent Injection for Mercury Control on Coal-Fired Power Plants," presented at the Nineteenth Annual International Pittsburgh Coal Conference, Pittsburgh, PA, September 23–27.

Schlager, R.J. (2002). "Mercury Control Pilot Testing at Brayton Point Station," presented at the Mercury Standards Technology Feasibility Meeting, Massachusetts Department of Environmental Protection, Boston, MA, September 20.

Senior, C., J. Bustard, M. Durham and K. Baldrey (2002). "Characterization of Fly Ash from Full-Scale Demonstration of Sorbent Injection for Mercury Control on Coal-Fired Power Plants," Air Quality III Conference, Arlington, VA, September 9–12.

Bustard, J., M. Durham, T. Starns, C. Martin, R. Schlager, C. Lindsey, K. Baldrey, L. Monroe, T. Coughlin, D. Johnson, S. Renninger and R. Chang (2002). "Full-Scale Evaluation of Sorbent Injection for Mercury Control on Coal-Fired Power Plants," Air Quality III Conference, Arlington, VA, September 9–12.

Bustard, C.J. (2002). "Activated Carbon for Mercury Control on Coal-Fired Boilers," Reinhold ESP/FF Conference, Dallas, TX, August 12.

Durham, M.D. (2002). "Update on Full-Scale Activated Carbon Injection for Control of Mercury Emissions," presentation to the Utility MACT Working Group, U.S. Environmental Protection Agency, Washington, DC, August 8.

Durham, M.D. (2002). "Field Evaluation of Mercury Control for Eastern Bituminous and PRB Coals," Coal-Gen, St. Louis, MO, July 31–August 2.

Bustard, C.J., M. Durham, C. Lindsey, T. Starns, K. Baldrey, C. Martin, R. Schlager, S. Sjostrom, R. Slye, S. Renninger, L. Monroe, R. Miller and R. Chang (2002). "Full-Scale Evaluation of Mercury Control with Sorbent Injection and COHPAC at Alabama Power E.C. Gaston," special edition *JAWMA*, **52**, pp. 918–926, August.

Starns, T., C.J. Bustard, M.D. Durham, C. Lindsey, C. Martin, R. Schlager, B. Donnelly, S. Sjostrom, P. Harrington, S. Haythornthwaite, R. Johnson, E. Morris, R. Chang and S. Renninger (2002). "Full-Scale Test of Mercury Control with Sorbent Injection and an ESP at Wisconsin Electric's Pleasant Prairie Power Plant," presented at the 95th A&WMA Annual Meeting, Session AE-1, Baltimore, MD, June 23–27.

Durham, M.D. and C.M. Martin (2002). "ADA-ES/DOE Mercury Control Program," presentation to Sargent & Lundy, Chicago, IL, May 31.

Durham, M.D. and C.M. Martin (2002). "ADA-ES/DOE Mercury Control Program," presentation to Washington Group, Englewood, CO, May 29.

Durham, M.D. (2002). "Control of Mercury Emissions by Injecting Powdered Activated Carbon (PAC)," presentation to the Utility MACT Working Group, U.S. Environmental Protection Agency, Research Triangle Park, NC, May 13.

Bustard, C.J. (2002). "Full-Scale Test of Mercury Control on Coal Fired Boilers," presented at the Western Coal Council Seminar on Burning PRB Coal, Louisville, KY, April 9.

Monroe, L. and R. Miller (2002). "Mercury and Utility Multi-pollutant Control," *Pollution Engineering*, pp. 42–43, April.

Krause, K. (2002). "Mercury Control, Sensible solutions that balance environmental risk and energy impacts," A&WMA *EM Journal*, pp. 22–28, April.

Senior, C., C.J. Bustard, M. Durham and K. Baldrey (2002). "Characterization of Fly Ash from Full-Scale Testing of Sorbent Injection for Mercury Control on Coal-Fired Power Plants," presented at Hg Control – The Effects on By-Products: What Do We Know and Where Do We Go?, U.S. DOE, Pittsburgh, PA, March 19.

Durham, M.D. (2002). "Full-Scale Demonstration of Mercury Control on Boilers Burning Bituminous and Subbituminous Coals," presented at Mercury – Consequences for Environment and Health, A&WMA, Montreal, Quebec, March 4–6.

U.S. Department of Energy (2002). "Advanced Mercury Control System's Performance is on Track, Test Shows," Fossil Energy TechLine, February 18.

Testimony on Compliance Options for Electric Power Generators to Meet New Limits on Carbon and Mercury Emissions, testimony given by Michael D. Durham to the Senate Committee on Environment and Public Works, Subcommittee on Clean Air, Wetlands, and Climate Change, Washington, DC, January 29, 2002.

Durham, M.D. (2002). "Status and Future Development of Mercury Removal Technologies," presented at the Building New Coal-Fired Generation Conference, Infocast, Phoenix, AZ, January 23–25.

Bustard, C.J. (2002). "Full-Scale Evaluation of the Injection of Activated carbon for Mercury Control for Eastern and Western Coals," presented at the Fifth Electric Utilities Environmental Conference, organized by EPA-DOE-EEI-EPRI-ETIC, Tucson, AZ, January 23.

Durham, M.D. (2002). "Results – Full Scale Evaluation of Mercury Control with Sorbent Injection and COHPAC on the Alabama Power E.C. Gaston Station," presented at the FOMIS Mercury Emissions Workshop "Maximum Achievable Control Technology…an O&M Perspective," Clearwater Beach, FL, January 21–22.

Durham, M.D. (2002). "Results – Full Scale Evaluation of Mercury Control with Sorbent Injection on a Unit Burning PRB Coal with an ESP at the Wisconsin Electric Power Pleasant Prairie Power Plant," presented at the FOMIS Mercury Emissions Workshop "Maximum Achievable Control Technology…an O&M Perspective," Clearwater Beach, FL, January 21–22.

Coughlin, T. (2002). "Operations, Maintenance and Monitoring Impact of Mercury Control with Sorbent Injection on a Unit Burning PRB Coal with an ESP at the Wisconsin Electric Power Pleasant Prairie Power Plant," presented at the FOMIS Mercury Emissions Workshop "Maximum Achievable Control Technology…an O&M Perspective," Clearwater Beach, FL, January 21–22.

Monroe, L. (2002). "Operations, Maintenance and Monitoring Impact of Mercury Control with Sorbent Injection and COHPAC on the Alabama Power E.C. Gaston Station," presented at the FOMIS Mercury Emissions Workshop "Maximum Achievable Control Technology…an O&M Perspective," Clearwater Beach, FL, January 21–22.

Bustard, C.J., M. Durham, C. Lindsey, T. Starns, K. Baldrey, C. Martin, R. Schlager, S. Sjostrom, R. Slye, S. Renninger, L. Monroe, R. Miller and R. Chang (2002). "Full-Scale Evaluation of Mercury Control with Sorbent Injection and COHPAC at Alabama Power E.C. Gaston," presented at the FOMIS Mercury Emissions Workshop "Maximum Achievable Control Technology…an O&M Perspective," Clearwater Beach, FL, January 21–22.

Schlager, R.J. (2001). "Experience with Mercury Control Systems for Boilers Burning Low and Medium Sulfur Coals," presented at the Clean Coal and Power Conference, Washington, DC, November 19.

Durham, M.D. (2001). "Mitigating Mercury Emissions from Western Coals," presented at the Western Coal Transportation Association Annual Meeting, Denver, CO, November 13.

Afonso, R. (2001). "Control Technologies for Reducing Mercury," presented at the New England Section of the A&WMA meeting, Worcester, MA, October 23.

Schlager, R., M.D. Durham, C.J. Bustard, R Schlager, C. Martin, S. Johnson and S. Renninger, (2001). "Field Test Program to Develop Comprehensive Design, Operating and Cost Data for Sorbent Based Mercury Control Systems," presented at DOE/China Clean Energy Technology Forum, Beijing, China, August 29–31.

Bustard, C.J., M. Durham, C. Lindsey, T. Starns, K. Baldrey, C. Martin, S. Sjostrom, R. Slye, S. Renninger and L. Monroe (2001). "Full Scale Evaluation of Mercury Control with Sorbent Injection and COHPAC at Alabama Power E.C. Gaston," presented at the A&WMA Specialty Conference on Mercury Emissions: Fate, Effects, and Control and The US EPA/DOE/EPRI Combined Power Plant Air Pollutant Control Symposium: The Mega Symposium, Chicago, IL, August 20–23.

Johnson, S., J. Bustard, M. Durham, S. Sjostrom, R. Slye, R. Afonso, C. Senior, A. Sload, M. Kane, D. Bondar, H. Stowe and S. Renninger (2001). "Mercury Measurements at Harbor Units 1 & 3," presented at the A&WMA Specialty Conference on Mercury Emissions: Fate, Effects, and Control and The US EPA/DOE/EPRI Combined Power Plant Air Pollutant Control Symposium: The Mega Symposium, Chicago, IL, August 20–23.

Martin, C., T. Starns, D. Johnson and S. Haythornthwaite (2001). "Full Scale Mercury Control on Pleasant Prairie Unit 2," presented at the A&WMA Specialty Conference on Mercury Emissions: Fate, Effects, and Control and The US EPA/DOE/EPRI Combined Power Plant Air Pollutant Control Symposium: The Mega Symposium, Chicago, IL, August 20–23.

Sjostrom, S., J. Bustard, M. Durham and R. Chang (2001). "Mercury Removal Trends in Full-Scale ESPs and Fabric Filters," presented at the A&WMA Specialty Conference on Mercury Emissions: Fate, Effects, and Control and The US EPA/DOE/EPRI Combined Power Plant Air Pollutant Control Symposium: The Mega Symposium, Chicago, IL, August 20–23.

Schlager, R.J. M. Durham, J. Bustard, C. Lindsey, T. Starns, K. Baldrey, C. Martin, S. Renninger, S. Sjostrom, R. Slye, L. Monroe and R. Chang (2001). "Mercury Control for Coal-Fired Boilers," presented at the 9th Annual Powder River Basin Coal Technical Conference, Gillette, WY, August 15–16.

Bustard, C.J. (2001). "Field Test Program to Develop Comprehensive Design, Operating and Cost Data for Sorbent Based Mercury Control Systems," presented at the Reinhold ESP/FF Roundtable and Exhibition, St. Louis, MO, July 24.

Durham, M.D., C.J. Bustard, R Schlager, C. Martin, S. Johnson and S. Renninger, (2001). "Controlling Mercury Emissions from Coal-Fired Utility Boilers: A Field Test," *EM*, pp. 27–33, July.

Durham, M.D., C.J. Bustard, R. Schlager, C. Martin, S. Johnson and S. Renninger (2001). "Field Test Program to Develop Comprehensive Design, Operating and Cost Data for Mercury Control Systems on Non-Scrubbed Coal-Fired Boilers," presented at the 2001 A&WMA Annual Meeting, Paper No. 24, Orlando, FL, June 24–28.

Sjostrom, S., J. Bustard, M. Durham and R. Chang (2001). "Mercury Removal Trends in Full-Scale ESPs and Fabric Filters," presented at the 2001 A&WMA Annual Meeting, Paper No. 471, Orlando, FL, June 24–28.

Schlager, R.J. (2001). "Mercury and the Future of Coal," presented at the Denver Coal Club, Denver, CO, May 10.

Durham, M.D. (2001). "Mercury Control for Coal-Fired Boilers," presented at the ICAC Annual Meeting, Dorado, Puerto Rico, May 3.

Bustard, C.J. (2001). "Mercury Control for Coal-Fired Boilers," presented at Burning PRB Coal: Risk Management Strategies and Tactics, Western Coal Council, Birmingham, AL, April 25.